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on

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WORKING GROUP 11

on

AIRCRAFT FIRE SAFETY

VOLUME 2: MAIN REPORT

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PREFACE

(1) Superior aircraft fire protection capability for civilian and military aircraft alike can be achieved only through continued research and development, implementation of international standards, test methods and procedures and, perhaps, most importantly through international exchange of all information related to aircraft fire safety.

(2) It was in this vein that the Propulsion and Energetics Panel of AGARD chose to play a role in this important field. As early as 1971, realizing that there was no archival literature for international meetings in the aircraft fire safety field, the Propulsion and Energetics Panel organized its 37th technical meeting in The Hague, Netherlands to deal with the subject of aircraft fuels, lubricants and fire safety. Nearly half the papers delivered at that meeting dealt with the fire concern. The interest generated at that meeting led this writer to organize a spontaneous ad hoc session on the need for fire research. The results of the meeting and the ad hoc discussion were reported in the Conference Proceedings AGARD CP-84, and Technical Evaluation Report AGARD AR-44.

(3) The Propulsion and Energetics Panel then devoted its entire 45th technical meeting in Rome in 1975 to the broad subject of aircraft fire safety. The Conference Proceedings AGARD CP-106 of this meeting have become a widely used reference volume in the field. But, more importantly, the enthusiastic response of the participants to the meeting and the obvious need for continued efforts and cooperation led PEP in September 1975 to establish Working Group 11 on Aircraft Fire Safety, the purpose of which was to make a comprehensive review of ongoing efforts, evaluate those areas of the field which require more attention, and to make recommendations of directions, procedures, actions, etc., for the common good. This volume is a result of the Working Group 11 effort.

(4) Although this writer, as a Member of PEP, was nominally Chairman of Working Group 11, personal circumstances prevented me from participating in a major way. The burden of organization, direction, writing and editing fell on Mr Ben Botteri of the US Aero Propulsion Laboratory.

Ben Botteri who was the Technical Director of the Group became the guiding spirit. To him, PEP and the whole aircraft fire safety community owe a great debt. We thank him and all his associates on Working Group 11 for their time, devotion and a job well done. Further, we must acknowledge Mrs Betty J.Baldwin of the US Aero Propulsion Laboratory for her outstanding secretarial assistance.

Irvin GLASSMAN
Chairman, Working Group 11

SUMMARY

The AGARD PEP Working Group 11 on Aircraft Fire Safety became functional in December 1976. The Working Group was tasked to analyze recent aircraft fire experience, delineate areas in which fire protection enhancement is needed, and identify technological opportunities that offer significant prospect for improvement of safety and personnel survivability. Because of the complexity of the overall problem and, the limited time schedule for completion, the Working Group focused its attention on turbine engine powered transport aircraft in a conventional (non-combat) operational environment.

Pertinent Working Group 11 conclusions and recommendations are summarized below. In the consideration of any of the recommendations, the Working Group strongly endorses a plan of execution which fosters cooperative international participation since, in many instances, implementation of promising approaches, once proven to be valid from an engineering viewpoint, shall require international acceptance.

A. Aircraft Accident/Incident Fire Experience - General Scenario

The major cause of impact survivable post-crash fires is fuel spillage from wing tanks, with the most disastrous consequences associated with wing separation, although tank penetration and rupture may produce similar consequences. Fuel line rupture at the engine or elsewhere is also common and has sometimes led to major post-crash fires.

Following initial fuel spillage, an enveloping mist of fuel which readily ignites is often caused by the aircraft motion, not necessarily disastrous by itself, but which can ignite subsequent fuel spillage. The resulting fire increases in intensity, possibly igniting other combustibles. Maximum intensity is reached in two to five minutes, after which the fire declines, although without fire-fighting services this phase may be prolonged. Fuel tank explosions occur on occasion, in about ten percent of fire accidents, and the main consequences are a great increase in the rapidity in which the peak intensity fire is reached, possibly with adverse effects on personnel evacuation. However, several minutes may clapse before explosion occurs, and there are examples of this occurring after evacuation has been completed.

Ignition sources are difficult to identify from accident narratives, although hot engine components and friction sparks from the impact appear to be commonly reported sources. It might be concluded if a fuel mist forms that some ignition source is almost inevitable.

Inflight fires are relatively rare (about 1/20th the probability of a serious accident compared with post-crash fires) and are usually controlled. This is especially true of engine fires which current protection systems cope with adequately. With only three dramatic exceptions, the same is true of cabin interior fires. Combustion of cabin materials may be significant in reducing survival time in post-crash fire accidents, but only marginally if major fuel spillage is fully ignited.

B. Aircraft Crash Fire Protection

Enhancement of crew and passenger fire survivability under impact survivable aircraft crash conditions represents the highest priority fire safety need. An agressive, multi-pronged program involving improvement of fuel containment, passenger life-support, and aircraft fire hardening and reduction of fuel ignitability is required. Additional specific pertinent determinations in major areas are as follows:

(1) Crashworthy Fuel Systems.

The primary problem lies in minimizing the effects of major fuel escape due to wing separation, tank rupture and fuel line failure. Crashworthy fuel systems, as developed for helicopters, cannot solve this problem except possibly to a very limited extent. It is recommended that consideration be given to improving the containment of fuel in fuselage tanks by a crashworthy system approach, together with the application of fail-safe couplings in the fuel system.

Some consideration should be given to the concept of designing the main wing tanks so that when wings separate in an accident fuel escape is, as far as is possible, avoided. For aircraft currently in operational use, such an approach is quite impracticable; nevertheless, the possibility of a major fire has to be considered and the survival of occupants may need to rely on prevention of fuselage burn-through by use of intumescent paints and similar measures. It is recommended that consideration be given to the incorporation of these features not only in aircraft currently in the course of design and to those in production, but also retrospectively to those now operational.

Modern low density void filler foams and intumescent coatings may help to retard the onset of catastrophic explosions to tanks exposed to fire; consideration should be given to the use of these materials and particularly to their efficacy in a real aircraft environment and after aging experienced during a life of many years use.

(2) Anti-Misting Fuel

Low volatility fuel of the Jet A/Jet A-1 type should be adopted for worldwide aircraft operations. It is recognised that continued use of Jet B fuel will be

required in certain locations where low temperature operations must be met. In conjunction with low volatility/fuel utilization, the anti-misting additive approach for reducing fuel ignitability under dynamic impact survivable release conditions should be vigorously pursued. In this regard, the Working Group strongly endorses the recently approved United Kingdom - United States aggressive joint program activity in this area. The potential benefits are considered to be substantial, particularly because of the potential for application to current aircraft. There may be circumstances, however, where no saving of life or property may arise, but the bulk of the evidence is advantageous. Problems do exist, however, with regard to the use of anti-misting additive both with regard to mixing and also degradation; until satisfactory solutions are available, anti-misting kerosene fuel use remains a prospect only. It's general application must depend finally on its international acceptance since it represents increased direct operating costs, offset only by the savings in insurance. In this respect, in view of the extensive studies and evaluations pertaining to modification of current jet fuel specifications to assure adequate future fuel availability for aircraft, integration of anti-misting and other fire safety considerations into the aforementioned activities could enable transition of a modified, safer fuel into operational use. This opportunity should not be overlooked.

(3) Inerting and Explosion Suppression Systems

In the crash situation the fire hazard exists mainly due to the release of fuel as a result of tank rupture and penetration. Where part of the fuel system remains intact, tank explosions can subsequently occur because of external heating and/or flame ingress effects. Under the latter conditions, inerting or other protection of the tank ullage should in principle be able to delay the onset of these secondary destructive explosions. Much work remains to be done, particularly by realistic tests, to confirm that the possible benefits can be achieved, before any positive recommendation regarding these systems can be put forward. The relative penalties and cost-effectiveness of the various protection techniques can then be evaluated allowing for possible additional benefits that may accrue. In the case of the inerting systems, the potential enhancement of inflight protection must not be overlooked.

(4) Fuselage Fire Hardening/Life Support

As we have indicated earlier, crashworthy fuel systems are impractical for current operational aircraft applications. Anti-misting kerosene, should it be shown to be feasible, could substantially reduce crash fire vulnerability but its general operational use is recognized still to be at an indeterminate future date. Consequently, for the near-term we are confronted with a status quo with respect to any enhancement of crash fire safety, unless we are willing to pursue less dramatic, but nevertheless meaningful incremental opportunities to enhance passenger survival.

When the fuselage is already ruptured or when doors and escape hatches are opened, the products of the external jet fuel combustion dominate the problem of survivability. Extension of egress/rescue time under such conditions is contingent on delaying or overcoming the hot toxic product gases debilitating effects. The only potentially practical near-term approach in this area is the availability of an individual life support hood with a portable, independent 3-5 minute air supply.

In the case where the fuselage is largely intact, it would appear that localized application of surface protective measures such as intumescent coatings, to hinder burn-through in sensitive areas, and the development of transparencies to resist sustained fire warrant consideration in addition to the aforementioned individual life support hood.

(5) Emergency Escape Improvements

Aircraft escape slides have saved many lives in the past; recent experience indicates, however, the problem of maintaining their integrity in a fire situation. Consideration should be given to improving the protection given by slides against the effects of fire and also to the maintenance of their structural integrity.

(6) Fire Fighting Improvements

Although not thoroughly assessed by the Working Group, the possibility of providing an improved fire fighting system from ground sources should be further examined. Proposals for example were suggested for filling the fuselage from external sources with water fog using the conditioned air supply ducts but this introduces other engineering problems.

Another major problem in the crash scenario is that of reduced vision due to smoke; any means of reducing this smoke would be beneficial. In this regard, the repositioning of emergency escape direction signs nearer the floor is recommended.

Another problem with rescue vehicles is in locating an aircraft in poor visibility, e.g., CAT III conditions. Guidance systems relying on the use of Airfield Surface Movement Indicator (ASMI) or homing equipment may be needed to enable them to operate effectively.

C. Inflight Fire Protection

Aircraft are potentially vulnerable to inflight fire and explosion as a result of on-board equipment failure, careless acts, e.g. improper disposal of smoking materials, or ignition threats posed by external sources such as lightning strikes. Although the overall inflight fire safety record is highly laudable, several major fire related accidents have been experienced in the period 1964-1974. These have included suspected lightning strike induced fuel tank explosions, fuel tank explosion induced by external heating for example by uncontrollable fire in an adjacent propulsion installation, and interior cabin fires. Additionally, numerous fire incidents have occurred where proper engineering design criteria, emergency actions and protection systems effectively limited the extent of damage and obviated any human injuries or fatalities. The overall accident and incident experience was assessed by the Working Group and provides the basis for the following conclusions and recommendations with respect to inflight fire scenarios.

(1) Engine Systems

Current fire protection measures offer a satisfactory high standard of fighting an engine fire contained within the nacelle. This no longer exists, of course, when the debris resulting from an engine break-up is not contained. Work should continue to reduce the frequency of noncontainment of debris and enhance the safety of the aircraft. It is unlikely that a complete solution to the problem will be possible and the aim must be to minimize the effects, should it occur, by suitable positioning of sensitive items and, where necessary, incorporation of additional protective measures. Similar concerns, preventive approaches and protective measures are also necessary with regard to the titanium fire hazard.

(2) Fuel Systems

Suspected lightning induced fuel tank explosions have all involved the more volatile Jet B type fuel or mixture of Jet B and Jet A fuels. These fuels are inherently more prone to generation of flammable vapor-air mixtures in the tank ullage under subsonic flight conditions. The lack of any mishaps involving straight Jet A type fuel appears to substantiate its safety advantage over Jet B under subsonic operational conditions. It must however also be emphasized that the extensive operational safety record with Jet B, both in military and civil aircraft, with respect to the lightning environment has been truly outstanding. The overall conclusion one arrives at is that valid engineering design criteria are being applied with respect to lightning protection and internal electrical system distribution. Advantages result from the continuous improvement in explosion resistance due to design progress, particularly in vent flame prevention, care in bonding, skin penetration, and use of intrinsically safe equipment within the tank. We must, however, not become complacent and improvements, where possible, should continue to be encouraged. It should be recognized, however, that future aircraft incorporating composite construction may be vulnerable and it is recommended that the effects of lightning strike should be examined for such materials.

With respect to protection of fuel systems from engine break-up continued consideration will have to be given to either positioning of the engines or armouring fuel systems against impact by any likely size of engine debris.

On-board inert gas generation systems currently under development provide an opportunity for additional enhancement of fuel tank protection which, in conjunction with other potential protection benefits offered, make their future consideration more attractive. Continued research and development activity consequently is strongly endorsed.

(3) Crew and Passenger Compartment

A major hazard reduction would arise if a no smoking rule were introduced and rigidly enforced. Since public opinion is unlikely yet to agree with such action, major protective measures should be employed in high hazard areas such as lavatories. These should be provided with automatic warning and extinguishment systems.

The presence of large quantities of combustibles carried by passengers, e.g., newspapers, hand luggage, coats and fluids containing alcohol, constitutes a serious potential fire source. It is recommended that serious consideration be given to minimizing this hazard for example by special on-board storage facilities. In addition, the current policy by some airlines of using large quantities of potentially hazardous plastic products for food and drink must be questioned.

Inflight fires also arise from the electrical system; short circuit protection, especially in air conditioning systems, requires reassessment and the consequences of aging on the integrity of electrical systems require review. Consideration should also be given to the incorporation of access ports to areas behind interior panels where electrical wiring is routed to enable localized application of a fire extinguishant such as Halon 1301 for emergency fire control.

Efforts should be made to ensure that the Crew Compartment will not suffer a high smoke concentration by suitable design and control of the air conditioning system.

The use of the oxygen system on existing aircraft should be immediately reassessed as a means of improving human survivability in the event of toxic smoke

invading the cabin. A standardized emergency procedure is required; the issue involves possibility of fire intensification versus passenger incapacitation from toxic combustion by-products. For the future, the concept of individual life support hoods for both crew and passengers deserves immediate attention, both for the inflight and post-crash fire scenarios. A multifunction hood is visualized which would be disconnectable from aircraft emergency oxygen system, and upon disconnect for egress purposes, provides a portable 3-5 minute air supply reservoir or source. With such as emergency life support hood, it should be possible to incorporate improved fire-retardant materials within interior cabin areas which otherwise would be unacceptable from a toxic product generation viewpoint. These materials, in addition to being more economical, would enable effective neutralization of the "flash-over" fire threat.

Apart from the deterioration by aging of electrical systems other non-metallics - oxygen systems, seat covers, and other furnishings - may similarly become less fire resistant with age. A research program to examine this situation should be carried out.

D. Ramp Fires

These generally occur either because of faults developing in the electrical system, the landing gear or during refueling operations; the latter has largely been eliminated by adherence to established fuel system design criteria, fuel servicing procedures, and in many countries by use of a static dissipator additive. The use of a static dissipator additive in aviation fuels is endorsed by the Working Group. The majority of recent electrostatic incidents during ground fueling have involved polyester polyurethane foam filled fuel tanks on military aircraft. Recent investigations have shown that direct impingement of fuel on these baffle materials results in localized electrical discharges which under proper fuel-air mixture conditions can trigger an internal combustion process. Because of the explosion protection offered by these baffle materials, these incidents have primarily entailed low order internal fire damage. Indications are that such occurrences can be essentially eliminated by modified fuel inlet and velocity criteria and, depending on the type of baffle foam, use of antistatic additive in the fuel. Since internal baffle foam is not currently utilized on civil transports, those aircraft are not affected by this potential problem.

Tire and wheel failures, however, which can lead to fires fed by the hydraulic system may lead to more serious disasters even if the ground fire services are quick to respond. The problems of hydraulic fluid flammability and the reduction in tire failures are both subjects where research could usefully be performed. Incorporation of sensors to monitor tire pressurization prior to take-off is also suggested as a mishap prevention approach.

When aircraft are unattended, consideration should be given to the provision of portable, automatic cabin fire detection and extinguishment capabilities in order to avoid extensive fire damage from comparatively minor fires being permitted to continue unabated.

E. Cargo Compartment

Cargo compartment fires can arise because of hazardous materials inadequately contained. Since no practical measures can totally prevent such fires, it is necessary to provide means of containing fires which do occur and isolating the compartment. In the consideration of the on-board inert gas generation system application, the benefit of providing cargo compartment protection should not be overlooked.

F. Testing

The overall excellent aircraft fire safety record manifests the benefits of extensive past testing, some of it triggered by unfortunate accidents. Much of the testing was in the category of engineering evaluations, i.e., investigation of the fire problem under specific high realism operational test conditions. Although a number of so called laboratory test methods have evolved and are in many instances economically essential, a large gap still exists in being able to correlate the results of a laboratory test or a combination of tests with the real world fire scenario. Consequently, the Working Group suggests that all of the various types of tests should be reviewed in the light of modern experimental and theoretical techniques to determine whether better tests can be devised.

(1) The tests themselves should be of sufficiently fundamental nature so that the experiments can be described analytically. If they are not, they should be modified or new tests devised.

(2) Within practical cost limits, modern experimental methods should be employed to produce not a single number, but a behavior pattern; not only a lumped parameter, but a detailed structure.

(3) Analytical models and techniques should be developed to relate laboratory test results to the full-scale problem. The nature of the tests and their interpretation must be developed together. The laboratory test results must provide the input data necessary for the analysis and therefore, cannot be selected arbitrarily. It would be useful, in fact, to analyze a fire risk problem and establish the type of tests necessary to provide quantitative evaluations and comparisons.

(4) Government laboratories and large industrial laboratories should continue to develop large-scale simulation facilities to provide a bridge between small scale laboratory tests and the full-scale problem.

(5) Wherever possible, accident data and full-scale tests should be used to refine the analytical models and guide laboratory test development. In this regard, participation of "a fire pattern expert" in aircraft accident investigations is strongly urged to assure comprehensive fire scenario or a "non-fire" scenario, as the case may be, analysis for meaningful input into model development and laboratory and full-scale test performance.

(6) With respect to combustion and pyrolysis by-products, animal testing is the only adequate technique to study toxicity although chemical analysis is useful. In this regard, semi- and full-scale testing relating to fire scenarios involving human exposure should always be conducted in an integrated manner, so as to yield both fire response and human survivability information.

The realization of these potential advancement opportunities in a timely and resourceful manner requires cooperative, international effort. In this regard, it is recommended that strong consideration be given to the establishment of a Systems Safety Panel under AGARD. A Safety Panel comprised of appropriate interdisciplinary representation is visualized to assure a suitable integrated engineering approach since fire safety is only one element of any overall system safety assessment.

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1. INTRODUCTION

1.1 Background

In April 1975 the NATO Advisory Group for Aerospace Research and Development (AGARD), Propulsion and Energetics Panel (PEP) conducted a very successful conference on Aircraft Fire Safety in Rome, Italy. One of the recommendations strongly voiced at the conference was that AGARD establish a Working Group to pursue a more in-depth study of aircraft fire safety with particular attention to the identification of specific problem areas and the formulation of a resourceful, cooperative research and development plan for addressing the higher priority needs. As a result, the PEP initiated action for the formal establishment of a Working Group which received approval of the AGARD National Delegates in the Fall of 1975.

1.2 Mission and Scope

The specific initial terms of reference for the Working Group are included in Appendix A. The Working Group membership (Appendix B) was finalized in late 1976 and held its initial meeting at AGARD, Paris, France in December 1976. At this meeting, considerable discussion took place on the definition of specific Working Group activities which would not only be of significance, but also attainable based on the expertise of the membership as well as the overall time period available for accomplishment. As a consequence of the above considerations, the Working Group agreed that three Subgroups dealing with Accident/Incident Experience, Combustion Hazard Analysis and Fire Protection Engineering, respectively, would provide the best suborganizational approach. Aircraft crash worthiness was included as an area of consideration under Fire Protection Engineering. With respect to the initial terms of reference, the Working Group also agreed that for the available period of performance and the diversity of potential fire scenarios that needed to be addressed, the scope of its activities as proposed in the original "terms of reference" should be limited to natural flight environment considerations. Consequently, specific attention to the specialized fire and explosion problems associated with combat (hostile) environment threats was deferred to a follow-on Working Group 11 activity or as the subject of an entirely new Working Group, whichever was deemed most appropriate by the AGARD PEP. As a matter of fact, with the exception of the fire initiation aspect, many of the fire propagation, sustenance and damage effects of the natural versus the combat operational environments are similar, and as a result, a "Bona Fide" exclusion of one from the other is not truly possible. In addition, when one endeavors to assess fire protection engineering measures, it is quickly apparent that new or novel approaches and in many instances practical use experience evolve first from military aircraft combat survivability enhancement efforts. To the above extent, at least, the Working Group endeavored to interject military aircraft fire hardening experience to the natural environment fire protection problems where applicable. Problems specific to commercial transport aircraft are the inflight fires caused by the careless use of smoking materials and the potential hazard resulting from the quantity of alcoholic beverages, newspapers and other items carried on board. In these respects commercial aircraft cabin fire experience is significantly different from that of military aircraft and, furthermore, passengers are generally untrained in their response to an emergency.

1.3 Approach/Working Group Organization

As indicated earlier, the general problem of Aircraft Fire Safety is very broad and complex, and consequently the Working Group had very early to define the extent of the problem that as a goal could hopefully be successfully pursued within the time frame desired by the AGARD Propulsion and Energetics Panel. From the very onset, the Group limited the area of principal emphasis to include natural flight environment and turbine powered transport aircraft. It was generally agreed that the transport type aircraft encompassed essentially all of the possible fire scenarios of potential interest and in addition, offered the best opportunity for gathering reasonably consistent accident/incident information on an international basis. A specific Subgroup was established to collect data on impact-survivable, inflight, and ground fire accidents and incidents which have occurred with civil and military turbine transport airplanes and, if feasible, helicopters and military tactical (non-combat) and training aircraft. In addition to providing direct data input to the Subgroups on Materials Combustion Hazards and Fire Protection Engineering, the mishap information was screened to enable formulation of representative fire scenarios for each accident/incident category and also to provide indicators of any deficiencies in fire accident/incident reporting methodology, the adequacy of current fire safety design and protection measures, the influence of fuel volatility and other materials, as well as the interrelationships between aircraft fire worthiness and airport crash fire fighting-rescue services.

A second Subgroup was established to perform an analysis of the combustion hazards of representative aircraft materials, both liquids and solids, in order to characterize pertinent ignition, flame spread, fire intensity, and toxic, flammable gas and smoke generation properties as influenced by pertinent current and projected operational environment utilization conditions. In addition, the Subgroup was to endeavor to develop fire spread models for solid and liquid combustibles and assess the adequacy of existing laboratory flammability test methods in terms of the aforementioned models. Research and development activities currently underway in the NATO Countries were also to be evaluated

and additional research or technological opportunities which, for example would enable improved combustion hazard risk assessment, development of less hazardous materials, and establishment of more meaningful combustion hazard testing dependent upon the major fire scenarios identified by Subgroup I and, in turn, was to serve as input to the fire protection engineering assessment.

A third Subgroup was structured to address aircraft fire protection engineering. This subgroup was to investigate the response relationships between realistic fire threat levels for aircraft inflight, ground and post-crash fires and key aircraft subsystems such as propulsion, fuel tanks, airframe and habitable environments. The approach was to entail identification, in a quantitative manner if possible, of rational survivability models encompassing varied, representative aircraft fire scenarios. Specific fire survivability enhancement techniques encompassing such strategies as the elimination of ignition threats; diminution of combustible material (solid and liquid) ignition susceptibility and flame propagation and sustenance behavior; the incorporation of early hazard monitoring techniques and active and passive fire and explosion protection measures for high risk fire scenarios; and the inclusion of adequate individual life support and escape capabilities under otherwise survivable fire hazard conditions, were also to be addressed. In the case of specific survivability enhancement techniques, the Subgroup was also tasked to provide at minimum a qualitative aircraft penalty assessment. Technological opportunities for realization of more acceptable fire hardening and protection approaches were also to be assessed.

Subgroup III endeavored to take note of the scenarios developed by Subgroup I and used by Subgroup II, however, in view of the peculiar characteristics of fires, which rarely fall into a common pattern, tended to follow an approach based on a continual reassessment of the situation.

2. AIRCRAFT ACCIDENT/INCIDENT FIRE EXPERIENCE - SUBGROUP I

2.1 Fire Hazard Ranking

A review of civil and military turbine aircraft accident and incident fire experience was performed and the following generalized scenarios of major civil transport aircraft fire threats were prepared based on the actual fire experience:

(1) Fires resulting from release of fuel due to wing separation during impact-survivable accidents.

(2) Fires due to release of fuel from damaged fuel tanks or fuel lines during impact-survivable accidents.

(3) Fuel tank explosions due to lightning, external heating, and other ignition sources under flight, crash, and parked conditions.

(4) Fires resulting from ignition of cabin interior materials under flight, crash, and parked conditions.

(5) Propulsion system fires.

(6) Landing gear system fires.

The fire scenarios are presented in Section 2.2 and may be used to provide guidelines for extrapolating laboratory fire test data to real situations and defining fire protection requirements.

Fire experience data, for the period 1964-1976, were obtained for civil turbine transport category aircraft and helicopters (air carrier and business operators) and military turbine transport, tactical, and training airplanes and helicopters which were involved in: (1) impact-survivable post-crash fire accidents, (2) inflight fire accidents and incidents, and (3) stationary and operational fire accidents and incidents on the airport. An impact-survivable post-crash fire accident in this study was defined as an accident in which some or all of the occupants survived the effects of the impact forces imposed during the crash sequence only to be subjected to the hazards of post-crash fire in evacuation from the aircraft. Inflight fire accidents were define as those which resulted in fatalities upon impact following loss of control due to fire or explosions or due to interior material fire prior to impact. When a fire resulted in minor damage without fatalities, it was defined as an incident.

The fire experience data base used in this study of aircraft fire safety was related to appropriate fire accidents and incidents that occurred within the Netherlands, West Germany, France, Canada, United Kingdom, and United States and to those accidents and incidents to aircraft registered in these states that occurred in non-participating NATO and non-NATO states. No attempt was made to obtain military aircraft combat fire experience. However, only a limited amount of sufficiently complete non-combat military aircraft fire experience data was made available for the study.

A total of 1141 civil and military aircraft fire accidents and incidents were reported for the period 1964-1976. This total included 212 impact-survivable post-crash fire accidents, 495 non-fatal inflight incidents, 38 fatal inflight accidents, and 396 airport accidents and incidents. Table 2.1 indicates the aircraft types that were involved in these accidents and incidents.

TABLE 2.1

Aircraft Fire Accidents/Incidents

Accident/ Incident / Aircraft Types	Impact-Survivable Accidents	Inflight		Airport Accidents/ Incidents
		Accidents	Incidents	
Civil Transports	51	6	33	98
Civil Helicopters	6	-	1	1
Military Transports	6	-	12	4
Tactical Aircraft	19	9	159	161
Military Trainers	4	5	247	122
Military Helicopters	126	18	43	10
TOTAL	212	38	495	396

Detailed narrative information for most civil transport aircraft fire accidents and incidents indicated in Table 1 was screened to identify the major fire threats. In addition to review of these data, fire accident and incident studies completed by other organizations were also reviewed to provide the overall basis for preparation of generalized scenarios of the major fire threats. These scenarios of the major fire threats were prepared in order to describe significant factors in the development of the fire from ignition to the conclusion of the fire event. Since narrative information was not available for most of the military aircraft fire accidents and incidents, it was not possible to describe any additional fire threats unique to military aircraft.

A thorough statistical analysis of the 1141 civil and military aircraft fire accidents and incidents was not performed in view of the lack of detailed information concerning most of the reports and the fact that the number of reports did not reflect the total number of fire accidents and incidents that occurred in each category. For example, Table 2.1 lists 51 impact-survivable fire accidents to civil transport aircraft from 1964-1976 while a review of world-wide accident records (reference 2.3 (1)) by the Coordinating Research Council (CRC) in the U.S. indicated that 97 impact-survivable transport aircraft fire accidents occurred between 1964-1974. However, it is of interest to note that identification of fire threats on the basis of analysis of the 51 fire accidents is generally supported by the more comprehensive accident analyses performed by other organizations.

It was estimated that fuel spillage occurred as a result of wing separation in about 59% of the 51 impact-survivable transport aircraft fire accidents shown in Table 2.1. This percentage is in general agreement with the CRC study which indicated that wing separation occurred in 49% or 48 of the 97 world-wide fire accidents. The nature of the fire threat resulting from fuel spillage due to wing separation was described by the Federal Aviation Administration (FAA) (reference 2.3 (2)) which reported that 19 of the 48 world-wide wing separation fire accidents were experienced by U.S. operators. Fourteen of the 19 wing separation fire accidents were fatal with an estimated 259 fatalities due to fire or its effects. Since there were 28 fatal impact-survivable U.S. transport accidents world-wide during 1964-1974 with a total of 987 fatalities, the 14 fatal wing separation fire accidents represented 50% of the total U.S. fatal/survivable accidents and the 259 fire fatalities in these accidents represented 26% of the total survivable accident fatalities.

The FAA estimated that 395 of the total 987 fatalities in the 28 U.S. transport aircraft impact-survivable accidents were caused by fire or its effects. These fatalities represent 40% of the total fatalities in these accidents and 23% of the occupants. The fuel fire and explosion threats created by fuel released due to wing separation were primarily responsible for 259 fatalities in 14 of these accidents. Fuel tank explosions in two of the wing separation accidents contributed toward the cause of 75 fatalities by expanding and intensifying the post-crash fires so as to prevent further safe evacuation. The 136 fire fatalities in the other 14 accidents were probably caused by the combined effects of fuel fires, explosions, and interior material fires. Fuel tank explosions in two of these accidents contributed toward the cause of 51 fatalities. On

world-wide basis, fuel tank explosions occurred in 11 impact-survivable accidents to civil aircraft from 1964-1974. These data indicate that spilled fuel fires, fuel tank explosions, and interior material fires are the major fire threats in impact-survivable accidents.

An analysis by the Civil Aviation Authority (CAA) in the U.K. of turbine transport accident experience with particular reference to crash fires (reference 2.3 (3)) indicated that there has been an increase since 1960 in the proportion of fatalities and in estimated fatalities due to fire in impact-survivable fatal accidents. This result is based on a relatively small sample of accidents as shown in Table 2.2

TABLE 2.2

Summary of CAA Impact-Survivable Fire Accident Analysis

	1960/64	1965/68	1969/72	1973/76
Fire Accidents	6	13	18	13
Est. Fatalities Due to Fire	86	280	427	526
- As % of Those Aboard	15	25	30	41
- As % of Total Fatalities	36	53	46	60

It is emphasized in the CAA analysis that these indications must be considered with the small accident sample taken into account. The CAA analysis further notes that world-wide scheduled air carrier services have been getting progressively safer since the number of fatal accidents each year has remained fairly steady over the last 20 years in spite of a 3 fold increase in aircraft miles per year and a 9 fold increase in passenger miles per year. It is concluded that it is about 2 1/2 times less likely today that a passenger will be involved in an impact-survivable fatal post-crash fire accident than it was in the early sixties.

Studies by other organizations have also provided additional statistical data on inflight fire accidents and incidents to expand upon the 6 civil transport inflight fire accidents and 33 incidents shown in Table 2.1. The CRC study (reference 2.1 (1)) reported that there were 5 civil transport and 3 military transport inflight fuel tank fire or explosion accidents world-wide between 1963-1974. The ignition of released fuel from ruptured engine feed lines occurred after the engine nacelles separated from the wing in two civil transport accidents. Fuel tank explosions occurred in these two accidents due to fuel tank heating from the engine feed line fires. Another civil transport inflight fuel tank explosion accident occurred as a result of heating by an engine fire. Lightning or spark-induced fuel tank or wing tip explosions occurred in two civil transport and 3 military transport accidents.

The FAA study (reference 2.3 (2)) referred to 7 civil transport inflight cabin fire accidents that occurred during 1967-74 of which one was fatal. Three inflight fire accidents involved battery compartment fires, two involved malfunctioning equipment fires, and two involved lavatory fires, one of which spread through the cabin and caused 123 fatalities. Two other fatal inflight cabin fire accidents were reported in this study and occurred as a result of ignition sources forward of the passenger cabin and in the aft section of the cabin. These three fatal interior material fire accidents resulted in 251 fatalities. These data indicate that fuel tank explosions and interior material fires are the major inflight fire threats.

Each individual fire threat was assessed on the basis of its potential for fire injury and probability of exposure to develop a ranking of the relative severity of the various fire threats encompassing the overall aircraft fire hazard. The likelihood of survival and the number of occurrences that were reflected in actual aircraft accident fire experience were considered in developing the ranking. If a fire threat is initiated by another fire threat, the initiating fire threat was judged to be more significant than the secondary threat. In view of these assessment factors, the individual fire hazards may be ranked in the order of decreasing significance indicated on page 8. Types of aircraft damage or operational modes are also indicated for each fire hazard in order of decreasing significance. Since the assessment factors were not weighted numerically the difference in significance between the various hazards cannot be expressed quantitatively, but fuel tank explosions and interior material fires are considered to be of almost equal significance as spilled fuel fires in impact-survivable accidents and interior material fires to be of almost equal significance as fuel tank explosions in inflight accidents.

Fire Hazard Ranking

1. Post-crash massive fuel spill fires.
   A. Wing/partial wing separation
   B. Major fuel tank damage

2. Fuel tank explosions.
   A. Inflight
   B. Post-crash

3. Post-crash moderate fuel spill fires.
   A. Minor fuel tank damage
   B. Fuel line damage

4. Cabin material fires.
   A. Inflight
   B. Post-crash

5. Propulsion system fires.
   A. Non-contained titanium fires
   B. Non-contained rotor fragment initiated fires

6. Landing gear system fires.
   A. Maintenance
   B. Inflight

7. Fuel tank explosions.
   A. Maintenance
   B. Refueling

The fire hazard pertaining to fuel release from wing separation was considered to be the major hazard because fires resulting from this mode of fuel release occurred in about 50% of the world-wide impact-survivable fire accidents. Fuel tank explosions were ranked as the number 2 fire hazard since 8 inflight explosions were experienced, several of which resulted in non-survivable impacts, and the explosions which occurred during post-crash fires in 11 accidents impeded further evacuation. The moderate fuel spill fire resulting from damaged tanks and lines was ranked number 3 because this fuel spill mode occurred in numerous accidents with a high percentage of fatalities caused by fire rather than impact. The number 4 fire hazard was considered to be due to cabin material fires because 3 fatal inflight fire accidents occurred and the contribution of cabin materials in certain post-crash fuel fire environments could be significant. Propulsion and landing gear system fires were ranked numbers 5 and 6, respectively, and the fuel tank maintenance and refueling explosion hazard as number 7 because these hazards have resulted mainly in aircraft damage and losses with few fatalities.

It was noted in this review of aircraft accident/incident fire experience that vital information relevant to aircraft fires was lacking from most accidents and incidents. Information on the cause and nature of aircraft fires would be of considerable assistance in designing preventive features and in research and development efforts directed toward reducing the fire hazards. It is suggested that a fire expert should participate in fire accident investigations to report on the fire and explosion aspects of an accident from a direct cause and/or post-crash fire viewpoint. Factors which would be of interest concerning an impact-survivable accident post-crash fire environment would include ambient air temperature, wind direction, engine RPM, flap position, impact speed, deceleration distance, fuel tank damage, fuel type, fuel temperature, ignition source, time of ignition, location, form, rate, amount, and area of fuel spill, crash site conditions, types of interior materials involved, and cause of fatalities. While it may not be possible to establish some of these factors in certain accidents, it would appear that reporting as much meaningful fire information as possible would prove valuable in efforts to reduce the aircraft fire hazards.

2.2 Generalized Aircraft Fire Scenarios (Based on Actual Accidents or Incidents)

2.2.1 Fires Resulting From Release of Fuel Due to Wing Separation During Impact-Survivable Accidents

Accidents have occurred where aircraft either undershot on approach or failed to become or remain airborne during takeoff and collided with structures, trees, drainage ditches, and other obstacles, resulting in wing separation and release of large quantities of fuel. The fire characteristics pertinent to this fire threat scenario are based on fuel release inflight prior to impact and/or during ground deceleration due to (1) initial fuel system structural damage of one wing followed by separation of the other wing and (2) separation of both wings or parts of both wings. The air shear forces imparted to fuel released in the dynamic phase of a survivable accident causes the formation of a fine mist of small droplets which is readily ignited, resulting in a fire which can envelop the aircraft and serve as an ignition source for continuing fuel spillage as the aircraft comes to rest. It is estimated that the duration of the dynamic phase may be up to 10 seconds, i.e., the period while the aircraft is in motion from the moment of initial damage resulting in fuel spillage until the aircraft comes to rest. Ignition sources during this period will include hot engine surfaces, internal

engine fire due to fuel ingestion, severed electrical wiring, friction sparks, hot brakes, and other sources which appear as progressive damage is inflicted. The fire developed during the dynamic phase serves as the ignition source for fuel spilled while the aircraft is at rest and for explosions in undamaged fuel tanks (reference 2.3 (4)).

The fire threat scenario resulting from the ignition of large quantities of fuel released under dynamic conditions may consist of several threats of steadily increasing intensity and severity. Fire broke out on the left side of the aircraft in a takeoff accident where structural damage was incurred in the left wing area, followed by a large fire which erupted on the right side of the aircraft after the right wing was torn loose, spilling the fuel contained therein. Several minutes after the accident occurred, two fairly large explosions occurred at the left side of the aircraft. Subsequent explosions occurred and hampered fire-fighting and rescue operations. An explosion also took place in another takeoff accident following wing separation as the aircraft struck railroad tracks. In approach undershoot accidents, fires have been initiated inflight following impact with structures and while passing through trees upon fuel spillage from severely damaged and separated wing tanks. These external fires move along with the aircraft as the aircraft come to rest and develop into intense ground fires which destroy the aircraft. A series of explosions occurred shortly after the aircraft involved in the approach inflight fire accident came to rest, expanding the fire so that further evacuation was impossible.

The effects of these fires are generally fatal before the cabin interior materials have a chance to generate lethal quantities of toxic gases and before fire-fighting and rescue services can arrive at the scene to assist any survivors of the impact.

A review of world-wide accident records (reference 2.3 (1)) conducted by the Coordinating Research Council indicated that 97 impact-survivable accidents occurred to civil turbine aircraft from 1964-1974 which resulted in spillage of fuel and post-crash fire. A Federal Aviation Adminstration (FAA) crashworthiness analysis indicated that 19 were experienced by U.S. operators (reference 2.3 (2)). Fourteen of the 19 U.S. wing separation/fire accidents were fatal with an estimated 259 fatalities due to fire or its effects.

The FAA crashworthiness analysis reported that there were 28 fatal impact-survivable U.S. air carrier turbine aircraft accidents during 1964-1974 with a total of 987 fatalities of which 395 were estimated on a conservative basis to be due to fire. A NASA analysis of aircraft accidents involving fires (reference 2.3 (5)) indicated that there were 314 fatalities which were definitely caused by fire in 11 fatal impact-survivable U.S. air carrier turbine aircraft accidents between 1964 and 1974 and 235 fatalities in post-crash fire accidents which were or could have been survivable. If it is assumed that all 235 fatalities in the latter accidents were due to fire, it was estimated that no more than 549 fatalities could have been due to fire. Therefore, the estimated 259 fatalities due to fire in the 14 U.S. wing separation/fire accidents represent 26% of the total survivable accident fatalities and 47-66% of the total estimated fatalities due to fire.

2.2.2 Fires Due to Release of Fuel From Damaged Fuel Tanks or Fuel Lines During Impact-Survivable Accidents

Fuel tank or fuel line damage has occurred in accidents which have occurred during the takeoff roll and landing run as a result of landing gear failure or impact with obstacles due to insufficient directional control and during approach and takeoff climb following contact with structures, trees, high ground, or other obstacles.

The possible effects of local damage to fuel tanks or fuel lines during impact-survivable accidents range from release of no fuel as some tanks may be empty to release of large amounts of fuel leading to fires approaching the severity described in the wing separation fire scenario. Fuel has also been released from damaged tanks without resulting in fire in non-fatal accidents. If the spilled fuel is ignited, the probable ignition sources are comparable to those in the wing separation scenario and will include hot engine surfaces, engine fuel ingestion, severed electrical wiring, friction sparks or hot brakes.

The fire characteristics pertinent to this fire threat scenario range from small fires fed by fuel released from slightly damaged tanks which are relatively easy to control to severe fires following massive tank damage which can eventually destroy the aircraft. Similar degrees of fire severity may be produced following damage to fuel lines caused by engine dislocation, engine failure, or landing gear failure as a function of elapsed time prior to shutoff valve actuation. The deceleration/impact forces in accidents resulting in fuel tank/line damage are usually less than in wing separation accidents so that the number of impact fatalities is less and the percentage of fire fatalities is higher.

Fuel was also released from damaged tanks in 13 of the 48 wing separation post-crash fire accidents which occurred world-wide to civil turbine aircraft from 1964-1974 (reference 2.3 (1)). Damaged tanks were the only sources of released fuel in 39 post-crash fire accidents in this period, while fuel as released from damaged tanks in

26 accidents where fire did not occur. Fuel was released from both damaged tanks and lines in 5 accidents where fire occurred and 4 accidents where fire did not occur and from only damaged fuel lines in 7 post-crash fire accidents and 4 non-fire accidents.

U.S. operators experienced 15 of the 39 damaged tank/post-crash fire accidents, 7 of which were fatal with an estimated 61 fatalities due to fire. These 7 tank damage/fire accidents represent 25% of the total fatal/survivable accidents experienced by U.S. air carriers during 1964-1974 and the estimated 61 fatalities due to fire represent 6.2% of the total survivable accident fatalities. Fuel was released from damaged fuel tanks without resulting in fire in 22 non-fatal accidents to U.S. operators. U.S. air carriers experienced two fatal fuel line or engine component damage/fire accidents in this period where all 91 fatalities were caused by fire and its effects. These two accidents represent 7.1% of the total fatal/survivable accidents and the fatalities due to fire represent 9.2% of the total survivable accident fatalities. The 152 fatalities due to fire in the 9 fuel tank/line damage fire accidents represent 62.8% of the total of 242 fatalities in these accidents.

2.2.3 Fuel Tank Explosions Due to Lightning, External Heating, and Other Ignition Sources Under Flight, Crash, and Parked Conditions

Fuel tank explosions have occurred inflight, during impact-survivable accidents, and while aircraft were parked due to a wide variety of ignition sources which appeared within the fuel tanks when the fuel vapor/air mixtures in the ullage were in the flammable range. The combustion reactions following ignition produced a rapid pressure rise inside the tanks which exceeded the structural limits and resulted in aircraft damage ranging from minor to complete destruction.

Integral fuel tank explosions inflight have occurred as a result of lightning strikes, external heating, and severed or shorted electrical wiring and have generally resulted in loss of control and a non-survivable impact. External tank explosions due to lightning have usually not resulted in loss of the aircraft. The lightning-induced fuel tank explosion scenario may be initiated by ignition of fuel vapor efflux from vent outlets near lightning strike attachment points and the subsequent propagation of flames through the vent system into the fuel tanks. It is possible for direct and swept lightning strikes to generate sufficient heat at attachment points on integral and external fuel tanks and produce hot spots or melt holes in the skin which could cause ignition. Transient voltages may be induced in the electrical wiring and components inside fuel tanks as lightning current is distributed between the entry and exit points on an aircraft. These inductive voltages can produce voltage breakdowns in components and wiring insulation which could also cause ignition. Internal fuel tank structural discontinuities and poor bonding can also cause sparking and ignition as a result of inductive voltages. Explosions in reserve, center, main, and outboard main integral fuel tanks of civil and military transport-type aircraft have been probably caused by some of these lightning ignition mechanisms and have resulted in explosive disintegration of wing structure followed by loss of control. Lightning initiated explosions in external and ventral tanks of military aircraft have generally not resulted in loss of control.

Other inflight fuel tank explosion scenarios may be initiated by heating of the fuel tank from engine compartment and pylon fires, penetration of the fuel tank by hot engine rotor fragments, and ignition of fuel released from damaged tanks by severed wiring. Engine and engine feed line external fires have caused high fuel tank surface temperatures resulting in autogenous ignition of flammable vapors and fuel tank explosions. Penetration of fuel tanks by engine fragments may also result in autogenous ignition of flammable vapors or ignition of released fuel from the ruptured tanks. In one accident where the aircraft took off following a hard touchdown during which an engine and pylon separated from the aircraft along with a piece of the bottom surface of a fuel tank, an explosion occurred in that fuel tank about 2 1/2 minutes after touchdown, followed 6 seconds later by an explosion in an inboard tank, and then by a third explosion which caused the loss of a large section of the wing. The combination of escaping fuel and the shorting of electrical circuits in a severed electrical harness may have been the primary cause for the first explosion which then caused the subsequent explosions.

Fuel tank explosions which have occurred during impact-survivable accidents have been caused by external fires fed by fuel released from severed wings, damaged tanks, or damaged fuel lines. These external fires create high fuel tank surface temperatures resulting in autogenous ignition or ignite the vapors in the vent outlet resulting in flames which propagate through the vent system into the fuel tanks. The explosions may expend the external fires and hamper fire-fighting and rescue operations in addition to creating non-survivable conditions which impede evacuation. A description of events leading toward post-crash explosions is presented in Scenario Number 2.2.1

Fuel tank explosions have occurred while the aircraft were parked and were being fueled or in connection with maintenance work being performed on the fuel system. The refueling explosions have been caused by ignition of fuel vapor due to a static discharge of an electrostatic field above the fuel. The maintenance explosions were the result of electrical arcs in fuel system components or fuel tank purging operations

where the blower used for purging the tank created a flame front which propagated into the tank. Fuel volatility has a major effect in these explosions since explosions with low volatility kerosene type fuels have usually resulted in minor to moderate aircraft damage while explosions with high volatility wide-cut fuels have usually resulted in major damage or total destruction (reference 2.3 (1)).

A review of world-wide accident records (reference 2.3 (1)) indicates that lightning-induced explosions occurred in the integral fuel tanks of one civil and one military transport-type aircraft with a total of 86 fatalities. The investigation of another transport accident is nearing completion where lightning-induced fuel tank explosions appear to be the most probable cause. A survey of lightning strikes to British RAF aircraft (reference 2.3 (6)) reported 46 strikes which involved external and ventral fuel tanks of which 12 resulted in fires or explosions, although no aircraft were lost. The world-wide accident survey (reference 2.3 (1)) also included a report of a non-fatal external tank explosion due to lightning on a military transport aircraft, two reports of integral tank explosions due to external engine fires, and the report of the inflight tank explosions following a hard landing which resulted in 109 fatalities.

Fuel tank explosions occurred in 11 impact-survivable accidents to civil aircraft from 1964-1974 (reference 2.3 (2)). These explosions were due to the ignition of vapors in a fuel tank vent by fire fed by fuel from a damaged engine fuel system component and heating of the fuel tanks by external fires fed by fuel released from severed wings, damaged tanks, or damaged lines. The fuel tank explosions in five of these survivable accidents contributed toward the cause of 131 fatalities by expanding and intensifying the post-crash fires so as to prevent further safe evacuation.

Fuel tank explosions in four incidents were caused by electrostatic discharge during refueling. Three aircraft were being fueled with kerosene-type fuel and suffered minor to moderate damage while one was being fueled with wide-cut turbine fuel and was completely destroyed. Fuel tank explosions during maintenance occurred to two civil and five military aircraft. Each involved wide-cut fuel and in all but two military cases the aircraft were totally or largely destroyed (reference 2.3 (1)).

2.2.4 Fires Resulting From Ignition of Cabin Interior Materials Under Flight, Crash, and Parked Conditions

Hazards have been created to occupant survivability due to the effects of fires resulting from ignition of cabin interior materials while in flight and in impact-survivable accidents. Inflight fire incidents and accidents have involved malfunctioning equipment fires (galley area, under the floor, battery compartment, behind the instrument panel) and lavatory fires, some of which have been fatal. Major post-crash external fuel fires can penetrate into the cabin in 40 to 60 seconds and may be generally fatal before the interior materials generate lethal quantities of smoke and toxic gases, but ignited materials can produce significant amounts of smoke and toxic gases to impede evacuation and cause fatalities. Interior fires which have occurred when the aircraft were parked or unattended were due to cigarettes in the cabin during cleaning, electrical ignition sources, and oxygen system failures and have resulted in extensive damage and hull losses.

Fatal inflight interior material fire accidents have occurred as a result of ignition sources forward of the passenger cabin, in the aft section of the cabin, and in an aft lavatory. One scenario was initiated by a short circuit between a battery terminal and its metallic cover at the battery location between the left pilot seat and the passenger cabin. The first indication was a release of smoke from the battery location after which the aircraft descended to 10,000 ft. A fire developed and expanded during this descent and the captain decided to crash-land the aircraft. During the final descent, the fire spread to the ceiling and aft to the passenger cabin, separating the cockpit from the cabin by a wall of flames. A survivable landing was made and the two pilots escaped through the right sliding window, but 28 passengers and the other crewmembers perished due to the high speed of the fire spread and associated smoke and toxic effects.

Another fatal inflight interior materials fire scenario was initiated by a fire which probably started in the right aft lavatory. A passenger noticed white smoke in the left aft lavatory but the smoke increased and became darker after a fire extinguisher was discharged in the left lavatory. The white smoke progressed very rapidly into the cabin along the ceiling and became black. The black smoke appeared almost simultaneously in the first class cabin and tourist cabin. About three minutes after the first report of smoke in the lavatory, the smoke broke into the cockpit and the pilots donned oxygen masks and smoke goggles and opened their sliding windows but the pilots could not see either the instruments or outside through the windshield. The pilot made a crash landing looking out through the open window. When the aircraft came to rest, flames were visible on the bottom of the aft left section of the fuselage. This fire finally broke out on the top of the fuselage in front of the verticle fin and consumed the entire fuselage interior. The combination of smoke and toxic gases resulted in asphyxiation of 123 occupants.

An interior material fire which resulted in loss of control and a fatal impact was probably initiated by failure of a water heater in the aft part of the

passenger cabin on the right side. It is possible that the fire was developing for a relatively long time before it was discovered at which time it was a heavy fire that spread through the aft wooden partitions and cabin upholstery and through the cabin ceiling. The loss of control may have been caused by inhalation of toxic gases by the crew or by failure of the flight controls.

An AGARD analysis by Snyder (reference 2.3 (7)) of NATO member air transport accidents, 1964-1975, revealed that injuries and fatalities were primarily due to the post-crash effects of fire, smoke and toxic fumes, and secondarily to crash impact. It was noted in this analysis that toxic gas emission from burning cabin materials has only recently had serious attention as a result of findings in several major accidents occurring within the past decade. Nine air carrier accidents were identified as being of particular note in this regard where the majority of the 356 fatalities have been attributed to the toxic effects of smoke and fumes or the thermal effects of fire. It was pointed out that in three of these accidents, 105 of 261 passengers aboard died in attempts to escape during the one to three minutes prior to the buildup of lethal thermo-toxic environment within the cabin. In four of the other accidents, significant amounts of hydrogen cyanide were found in victim blood levels which attests to the fact that aircraft materials contribute to the lethality of the smoke in some post-crash aircraft fires, since burning fuel alone would not produce cyanide (reference 2.3 (8)).

Scenarios which are intended to describe the contribution of interior materials to the post-crash fire hazard are difficult to prepare since appropriate data are scarce by which to separate the effects of burning fuel and burning materials. The influence of burning materials on survivability and evacuation is also interrelated with the extent of structural damage, impact injuries, discipline and order among the crew members and passengers, and whether the accident occurred at night or in daylight. While accident reports have shown that smoke and toxic gases can impede evacuation and have an incapacitating effect on occupants, details with respect to the quantities produced by interior materials in the accident environment and the interrelationship with other factors are generally not available.

However, some indication of the hazard of burning cabin materials has been provided by full-scale fire tests. Such tests have shown that a relatively small materials fire can fill a passenger cabin with dense black smoke quickly. In one of the tests, a firepan containing one quart of jet fuel was ignited beneath a passenger seat. In about 1 3/4 minutes, the smoke generated by the burning fuel and passenger seat was so dense and black that observers were unable to see the seats or the fire only a few feet away. In a similar follow-up test using smokeless alcohol instead of jet fuel, it took about 4 1/2 minutes to reach a similar smoke level of total obscuration. While the fuel smoke predominated over materials smoke in these tests, to total obscuration by smoke produced by this small fire condition far exceeded that level which could impede evacuation. Based on test results such as these, a scenario can be developed in which the aircraft cabin becomes filled with smoke and toxic gases from burning interior materials as a result of a post-crash fuel fire. In this scenario, an external fuel fire burns through the aluminum skin and impinges on the cabin interior lining materials. The heat flux of this fuel fire impinging on the cabin interior lining and other materials could generate large amounts of smoke and toxic gas emissions from the materials which fill the cabin and create intolerable conditions concerning survivability and evacuation (reference 2.3 (9)).

Interior material fire incidents have occurred while aircraft were parked unattended as a result of electrical ignition sources and oxygen system failures during servicing. Fires have originated inside aft lavatories from electrical overheating and/or arcing at the electric shaver outlet and water heater, at a cove light due to a capacitor failure, behind the overhead coat rack area due to an electrical short, at the center seat area, and behind the oxygen system service panel. These fires spread throughout the cabin and ignite interior materials and produce dense smoke which serves to notify airport personnel of the fire. The interiors of the aircraft involved in these incidents were destroyed by the time the fires were extinguished.

The three fatal inflight interior material fire accidents described herein resulted in 251 fatalities. It is not possible to estimate the fatalities attributable to burning cabin materials in most of the past impact-survivable accidents, but the overall effects of fuel and material fires were estimated to be the cause of 395 fatalities in the 28 world-wide fatal impact-survivable U.S. air carrier turbine aircraft accidents which occurred during 1964-1974. These fatalities represent 40% of the total fatalities in these accidents and 23% of the occupants (reference 2.3 (2)).

There were 5 major interior material fire incidents in the U.S. during 1964-1974 and several in Europe which occurred while the aircraft were parked unattended.

2.2.5 <u>Propulsion System Fires</u>

Modern civil transport aircraft exhibit a wide variance in engine/airframe installations. These include wing-pod mounted, fuselage-pod mounted, and combinations of internal aft fuselage and wing or fuselage-pod mounted configurations. Major engineering attention is given to these propulsion areas to: (1) surround the fire zones with fire proof materials so as to confine a fire and prevent its penetration into

adjacent unprotected compartments, (2) provide for rapid detection of a fire, (3) allow for shutting off the flow of flammable fluids and (4) extinguish the fire. Limitations of such protection, shown by operational experience, are that no effective control of fire can be assured if the boundaries of the fire zones are breached or if the crew fails to activate shutoffs promptly. Compromise of fire zone boundaries has occurred due to internal engine failure (fan blade separation, compressor and turbine stage failures) resulting in penetration of the engine case and adjacent fire wall of airframe structure. Location of fuel tanks within the failed engine - projectile pattern aggravates the resulting fire severity by generation of an uncontrollable fuel leakage situation and the possible direct or secondary initiation of internal fuel tank fire and/or explosion. Particular engineering design considerations must be pursued to reduce the fuel tank vulnerable area in the event of catastrophic engine failure. Based on typical aircraft engine/airframe installations, it is evident that propulsion system fire scenarios must provide attention to the fire threat external to the engine, within the designated fire zone area, and also to the engine internal failure induced fire situation. The latter must include consideration of engine response due to fuel ingestion, internal oil leakage, and the combustion/fire characteristics of internal engine components (fan and compressor blades, etc.) under dynamic frictional loading conditions.

The propulsion compartment fire scenario which is the one most frequently experienced is one wherein the engine and nacelle structure are essentially intact and fire results from leakage of a combustible fluid (fuel, oil, hydraulic) and ignition by the hot surface of the engine. The likelihood of ignition occurrence depends upon a number of factors including the nature of the fluid, its dwell-time which is a function of ventilation within the compartment, air temperature and air pressure, etc. Upon ignition sustenance of the combustion process requires continued supply of fuel as well as configurational/flow conditions conducive to flame attachment within the nacelle. The fuel-air combustion process is of the diffusion type involving fuel leakage, vaporization and mixing with air. Leakage conditions because of the pressurized combustible fluid lines, can be of the atomized spray variety and thereby more closely approach a premixed flame process. The maximum heat generation for a typical hydrocarbon combustible fluid assuming an overall stoichiometric combustion process is approximately 3.012×10^6 joules/kg. - air (1295 BTU/lb-air). Because of the diffusive nature of the combustion process, overall average flame temperatures based upon full-scale engine nacelle fire tests do not exceed 1094°C (2000°F). Consequently, containment of such fires requires judicious use of materials which can maintain integrity under anticipated heat flux and temperature conditions in critical areas (both internal and external to the nacelle). This has resulted in the standard requirement for fire walls made of materials such as stainless steel and/or titanium which possess high melting points and sufficient strength at elevated temperatures. Additionally, fire control demands the ability for early warning of presence of fire; means for shut-off of all combustible fluids flow; and effective means for fire extinguishment. The combustible fluid shut-off and extinguishment actions must be taken rapidly since any extensive delay results in general heating of structural elements resulting in reduced effectivity of the extinguishant as well as increased probability of reignition of residual fuel once the extinguishant is dissipated. In general, based on experience, aircraft fire protection engineering capable of coping with the intact-engine nacelle fire scenario is adequately established.

A second fire scenario depicts situations wherein two failures, one to provide the source of ignition and the second to furnish the source of combustible, are required to generate a sustained fire condition. The specific triggering failures at least initially occur with the nacelle fire containment design features uncompromised. These failures are engine combustor-can burn-through and high temperature, high pressure bleed air duct failure. Combustor-can failure results in a highly localized high temperature jet (>1538°C) (>2800°F) which, depending on its proximity to critical structural members and fluid containing components, can cause additional failures and penetrations with consequent growth of the hazard condition to total fire involvement, but with the possibility of the fire wall having been compromised. Bleed air duct failure also can provide a high temperature (482 to 649°C) (900 to 1200°F), high pressure (5-6 atm), high mass flow air source which can result in damaging effects to structural and equipment components in the nacelle. The hot air source is capable of igniting combustible fluids and upon ignition can generate a very intense combustion process possibly exceeding or taxing fire protection design criteria normally applied to propulsion installations. Reducing the severity of nacelle fire damage as well as likelihood of penetration through fire walls into other areas of the aircraft requires early detection capability, and shut-off of the hot gas source via engine shut down or bleed air shut-off. Following this action, if presence of fire is still indicated, activation of the fire extinguishing system generally should be able to cope with the problem.

A third fire scenario is triggered by an internal failure of the engine resulting in discharge of engine parts (fan, compressor, turbine) through the engine case into the adjacent nacelle area and other aircraft compartments adjacent to the nacelle boundary. The high velocity metal fragments behave very similar to ballistic rounds and exhibit good penetration capabilities with the attendant generation of high intensity friction sparks. The failure consequently provides a high probability of penetration of combustible fluid lines as well as any fuel tanks which may be in the projectile path. This rapid sequence of events involving ignition source generation coincident with combustible fluid leakage offers a high probability of fire with compromised fire containment capability and, if close to fuel tanks, compromise of fuel shut-off capability, any of which can lead to defeat of the fire protection posture and result in loss of aircraft.

A fourth fire scenario refers to another internal engine failure mode which is triggered by ingestion of combustible material (fuel, hydraulic fluid, oil, particulate solids). The process is basically one where fuel is introduced directly into the inlet air and is carried through the compression cycle with resultant increase in pressure and temperature to the point where compression ignition can occur with consequent significant further increase in pressure and temperature and resultant rupture of engine, stalling and belching of the engine, and internal rotating component breakup. Basically, the process is one of internal explosion. This failure sequence can occur due to internal oil leakage, rubbing of parts with resultant generation of combustible particulates, or ingestion of fuel into the engine. The latter fuel ingestion problem could be experienced during crash-landing of aircraft resulting in rupture of fuel tanks and coincident fuel ingestion into the engine. The quantity of combustible fluid required to cause a catastrophic engine response will vary with engine size but is relatively small (few pints per second).

A fifth fire scenario represents another manifestation of internal engine failure via rapid internal engine fire propagation involving materials of construction, particularly titanium and titanium alloys. Titanium alloys in recent years have been widely applied to turbine engine compressor parts. A number of factors are involved in this trend; the most notable of which is the increase in the thrust-to-weight ratio of current engines. Lower weight demands a more flexible engine and lighter components and these factors when added to the desire for more thrust, result in increased pressure, temperature and flow providing an environment conducive to ignition, self-sustained combustion and propagation of a titanium fire. The fires have been generally caused by titanium rubbing on titanium primarily as a result of compressor blade, disk, and rim failures and blade tip rubs with the casing. When a titanium blade is heated by rubbing, or as a result of a blade fracture, it will ignite before it melts and sustain burning until pressure and air velocity conditions are reduced below the necessary range or until the titanium is consumed. Titanium fires are fast burning, i.e. 20 seconds or less, and are extremely intense. The molten particles in titanium fires generate highly erosive hot sprays which have burned through compressor casings with resulting radial expulsion of molten or incandescent metal. Damage from these fires has ranged from contained blade burning to 360° penetration of the casing and penetration of external flammable fluid lines. This could lead to a secondary fire in the engine compartment as a result of damage to the fuel and oil lines. Engines with titanium rotors, stators, and casings have experienced titanium fires since the mid-1950's during ground tests and inflight. While titanium engine fires have resulted in substantial engine and compartment damage, there is no record of a fatal accident being caused by a titanium fire in civil air carrier operations.

2.2.6 Landing Gear System Fires

Accidents and incidents involving landing gear system hydraulic fluid fires have occurred during all phases of ground operations and inflight. Ground fire accidents and incidents have been caused by dragging brakes, wheel failures, blown tires, hydraulic fluid leaks and collapsed landing gears following hard landings. Inflight fire incidents have resulted from tire explosion, hot brakes, and wheel well hydraulic system failures.

A collapsed landing gear ground fire scenario was initiated when an aircraft made a firm landing on the nose gear first which caused the nose gear and wheel well structure to be pushed aft and upward into the fuselage. Fire erupted in the lower electronic bay area beneath the floor of the flight deck which was fed by hydraulic fluid from two fractured nose wheel steering hydraulic lines. The fire was not contained and eventually destroyed the interior of the cockpit and passenger cabin. Another landing gear ground fire scenario was caused by tire failure during the takeoff run which prompted the crew to reject the takeoff. Pieces of burst tires and/or wheel rims had damaged the hydraulic lines on the landing gear strut and the elevated brake temperature or wheel friction sparks ignited the released hydraulic fluid. When the airplane came to rest, there was a small fire at the front tires of the landing gear. The hydraulic fluid spread and the fire enlarged such that smoke penetrated into the cabin 6 minutes after the airplane had stopped. After another 6 minutes, the fire had caused the fuselage to fail and the tail section touched the runway. The fire continued to burn for more than 8 hours and almost totally consumed the airplane.

A landing gear inflight fire scenario was initiated when a hydraulic fluid fire developed in the left wheel well when the landing gear was lowered for landing. The left engine was shut-down and the fire extinguisher was discharged but the fire continued to burn and the hydraulic system failed. The aircraft veered to the right after touchdown, collapsing the left gear. The fire which had continued burning was extinguished by the fire department. Another inflight fire scenario was experienced by a military cargo transport airplane when hydraulic fluid in the left aft main gear compartment was ignited by hot brake surfaces. Burning of the hydraulic fluid resulted in ignition and burning of the tires in the compartment. The tires were the major source of fire and caused burning of wires and seals and melting of aluminum lines, components, and structure. These components carried hydraulic fluid and their failure resulted in additional fluid being added to the fire. The increase in severity of the fire resulted in burn-through of the keel and fire propagation into the right aft main gear compartment. There was fire on both sides of the aircraft just prior to landing. After landing, the engine fuel shutoff valves were actuated but one valve may have been

damaged during impact and allowed fuel to be released which contributed to the post-crash fire that started about 20 minutes after the aircraft came to rest. Fire severely damaged the forward section of the fuselage and wings.

From 1973 through 1975, U.S. operators experienced 8 accidents and 22 incidents involving landing gear system fires. Aircraft damage in these fire accidents ranged from minor to almost complete destruction. While there were no fatalities, numerous injuries were sustained by occupants during emergency evacuations.

2.3 References

(1) Coordinating Research Council. Aviation Fuel Safety - 1975. Report No. 482, November 1975.

(2) Horeff, T. G., A Crashworthiness Analysis with Emphasis on the Fire Hazard: U.S. and Selected Foreign Turbine Aircraft Accidents 1964-1974. Federal Aviation Administration, Washington, D.C., Report No. FAA-RD-75-156, July 1976.

(3) Black, H. C., Civil Aviation Authority. Jet Airplanes - A Summary of Accident Experience with Particular Reference to Crash Fires. Presentation at Public Hearing on Transport Category Airplane Post-Crash Fuel System Fire and Explosion Hazard Reduction, Washington, D.C., 13-17 June, 1977.

(4) Cohn, B. M., and Campbell, G. A., Minimum Needs for Airport Fire Fighting and Rescue Services. Federal Aviation Administration, Washington D.C., Report No. AS-71-1, January 1971.

(5) Lucha, G. V., Roberston, M. A., and Schooley, F. A., An Analysis of Aircraft Involving Fires. NASA Ames Research Center, Moffett Field, CA., Report No. NASA CR 137690, May 1975.

(6) Royal Aircraft Establishment. Ignition of Aircraft Fuel by Lightning and Electrostatic Charge. Unpublished Document YSH/361/03. 18 July 1977.

(7) Snyder, R. G., Advanced Techniques in Crash Impact Protection and Emergency Egress from Air Transport Aircraft. AGARDograph No. 221 (AGARD-AG-221), June 1976.

(8) Kirkham, W. R., and Lacefield, D. J., Civil Aeromedical Institute, Oklahoma City, OK, correspondence to Sullivan, W. J., Federal Aviation Adminstration, Washington, D.C., 28 November 1977.

(9) Branting, H. P., Federal Aviation Administration, Washington, D.C., Unpublished Document, 12 December 1974.

3. AIRCRAFT MATERIALS COMBUSTION HAZARD EVALUATION - SUBGROUP II

3.1 Background

The decomposition and burning of aircraft materials is the crux of the fire safety problem. In addition to the fuel, which represents the largest quantity of combustible, the various fluid systems, organic materials, and the structural materials themselves may initiate or support a fire. The improvement of fire safety can be brought about in two ways, either separately or together: (1) alter the materials or material properties and/or (2) alter the environment in which the materials are used.

In an examination of the scenarios which are considered representative of the majority of fire in aircraft, it is possible to relate the major involvement of materials, ignition sources, and the laboratory tests which are relevant to fire hazard evaluation.

Fires originating external to the aircraft cabin include, generally, crash fires, fuel tank explosions, engine fires, and fires associated with the fuel system, hydraulic and oil systems. The flammables which may be involved are: (1) fuel, (2) hydraulic fluid, (3) lubricants, and (4) structural materials, tires, etc. The ignition sources likely to be present are: (1) hot surfaces and hot gas jets, (2) electric sparks, (3) static electricity, (4) friction spark, (5) flames (engine torching, etc.), and (6) lightning.

Fires originating within the cabin generally involve widely different types of combustible materials ranging from the "empty" contents which include all interior fixtures, trim, supplies, etc., to the "full" contents which include the variety of combustibles associated with the passengers and their carry-on materials.

References can be found in Section 3.8.

The ignition sources likely to be present are: (1) electrical sparks, (2) hot wires due to electrical failure, (3) matches and cigarettes, and (4) hot surfaces.

Since it is not feasible to build complete systems and study all modes of failure and all existing and proposed materials to determine the degree or nature of a fire hazard and the extent to which design or materials changes affect the fire hazard, laboratory tests have been devised. Some of these tests have a strong fundamental basis and measure chemical and physical properties of the material while others are strictly empirical and the test results are strongly dependent on the nature of the test apparatus and procedure. Many laboratory tests are as complicated to analyze as the full-scale problem they attempt to simulate and are merely smaller in size. Even such tests can be made reproducible by careful attention to experimental detail. In some cases, the data produced are treated as properties of the material although the results are clearly apparatus dependent.

A fire is a very complicated event and a multitude of different fire scenarios can exist. It is evident that a single data point or rating cannot adequately describe the behavior of combustibles in all actual fire situations. Some tests give conflicting results when the data are treated only as means of rating materials. Two fuels are compared in Table 3.1 on the basis of thermal ignition temperature and flash point.

TABLE 3.1

Comparison of Two Fuels

Fuel	ASTM AIT, °C/°F	Flash Point, °C/°F
Gasoline	451/844	-40/-40
Kerosene	227/440	38/100

Which is the safer fuel? Gasoline produces a flammable vapor under the conditions of the flash point measurement at temperatures above -40°C, while kerosene requires temperatures in excess of 38°C/100°F. On the other hand, kerosene ignites more easily when exposed to a hot surface in the experimental configuration of the ASTM test. It is evident that a list of AIT's and/or a list of flash points is inadequate to assess aircraft materials combustion hazards although both are widely used laboratory tests. In order to evaluate aircraft materials combustion hazards one must have methods of testing material properties and, equally important, techniques for relating the test results to the full-scale fire problem. In most cases, we are not able to accomplish this task and a need exists to reexamine the entire concept of laboratory scale materials testing. The examination should begin with an evaluation of the material properties which influence fire safety. Tests should be devised which supply the needed data. These tests, in themselves, should be created in a manner which permits analytical description to facilitate the extension of the test results to a variety of conditions and, hopefully, to the full-scale problem.

Laboratory tests have been developed which address all of the ignition sources discussed in the fire scenarios as well as the problems of smoke and toxicity associated with the thermal degradation and/or combustion of cabin materials. In the sections which follow, a brief description of laboratory tests associated with: (1) liquid volatility, (2) thermal igntion, (3) spark ignition, (4) cabin materials, and (5) fire intensity are discussed. No effort has been made to include all existing tests or to present a handbook of materials properties. The purpose of the discussions which follow is to illustrate typical data and, in some cases, the deficiencies of current test methods.

3.2 Aircraft Fluids

3.2.1 Volatility Factors

It is well-known that ignition and fire spread are affected by the volatility of the liquid combustible. The exact effects, however, are not always obvious and the proper definition or measurement of volatility is not always simple for the complex mixtures which form the commercial fuels, lubricants, and hydraulic fluids in actual operation. In addition, some of the combustion tests are strongly dependent on fuel volatility. Both topics are reviewed briefly in this section.

3.2.1.1 True Vapor Pressure

There is no problem in defining the vapor pressure of a pure substance; this property is a function only of temperature for an ideal fluid, is easily measured, and provides a meaningful quantity for fuel-air ratio calculations. The situation is more complicated for mixtures since the pressure measured is a function not only of temperature, but also of the volume of the system or the quantity of fuel evaporated. One can define a quantity, the so-called "true vapor pressure" measured under conditions such that the vapor volume is sufficiently small so that the amount of liquid evaporated is negligible and the liquid composition remains unchanged. The vapor composition is generally quite different from the liquid composition. The true vapor

pressure is a useful property of a mixture, but is of little value in many fire hazard evaluations since it does not represent the most likely situations where appreciable liquid has evaporated.

3.2.1.2 Reid Vapor Pressure

In order to establish a reproducible method for comparing the volatility of fluids, measurement techniques which carefully control the liquid-vapor volume ratio have been developed. Of these, the Reid vapor pressure is the most common. In this technique, the pressure of the fluid is measured at 38.5°C/100°F in a bomb in which the initial fluid volume is approximately one-fourth of the air volume. Reid vapor pressures can be measured reproducibly but, again, the liquid-vapor volume does not necessarily correspond to conditions under which a fire hazard evaluation is made. The Reid vapor pressure is also different from the true vapor pressure since some of the fluid evaporates and a change in the liquid composition may result.

3.2.1.3 Distillation Curve

In order to provide an estimate of the quantity of fluid evaporated in different temperature ranges, a distillation curve is established on the basis of a standard procedure.

A measured quantity of fluid is heated at a prescribed rate and the percent evaporated is determined at average temperature points. On the basis of distillation curves, it is possible to estimate the vapor concentration at various liquid temperatures. The temperature is also an indication of the mean molecular weight of the evaporated fluid and assists in the calculation of vapor fuel-air ratios. While such curves are a step in the right direction in providing useful data on fuel volatility, the lack of time dependent basis and the lack of correspondence of the heating rate to a specific hazard analysis leaves much to be desired. Examples of some typical distillation data are given later.

3.2.1.4 Relationships Between Volatility Parameters

Relationships exist between the Reid vapor pressure and the true vapor pressure as well as to parameters calculated from the distillation curve.

$$P_R = S \frac{a}{\rho_R t_{10} + b} + C$$

P_R = Reid vapor pressure, #/sq.in. = 6.895 P_R, Pascal

S = slope of ASTM distillation curve at the 10% evaporated point. $S = (t_{15} - t_{15})/10$

$t_{20}, t_{15}, t_5 \ldots$ = temperature on ASTM distillation curve for 20%, 15%, 5%...evaporation

ρ_R = density at 16°C/60°F of liquid fuel

a,b,c = empirical constants which depend on fuel, examples in table below.

Fuel	a	b	c
Avg. Gas	486	-50	-4.33
JP-4	114	-89	-.45

$$P\ 38.5/100\ (\text{psi}) = P_R + 0.0223\ P_R + \frac{0.0119\ P_R S}{1 - 0.0368\ P_R}$$

$$P\ 38.5/100\ (\text{Pascal}) = 6.895\ P\ 38.5/100\ (\text{psi})$$

$$P\ 38.5/100 = \text{true vapor pressure at } 38.5°\text{C}/100°\text{F}$$

"True" vapor pressures at other temperatures can be estimated by means of the Clapeyron equation.

3.2.2 Combustion Parameters

In order to discuss some of the combustion parameters which depend on volatility, it is convenient to summarize the significance of the flammability limits. The lean flammability limit, also called lower explosion limit, is determined by the lowest concentration of fuel vapor in air (or other oxidant) which will permit flame propagation. The rich flammability limit or upper explosion limit is a measure of the maximum concentration of fuel vapor in air (or other oxidant) which permits flame propagation. Mixtures with a lower fuel concentration than the lean limit are considered too fuel lean to burn and mixtures with high fuel concentration than the rich limit are considered too fuel rich to burn.

It is evident that if the source of fuel vapor is a liquid fuel, the volatility or evaporation characteristics of the fuel will determine whether a mixture capable of propagating flame can exist.

3.2.2.1 Flash Point

The standard test which has been used to establish the temperature at which a liquid produces a vapor mixture greater than the lean limit is called the flash point. In this measurement, liquid is placed in a cup to a given level allowing a fixed vapor volume. The temperature of the liquid is controlled until a critical value is reached, below which the vapor does not ignite when exposed to a test flame and above which ignition does occur. The separating temperature is called the flash point.

Although the experiment does not correspond to the flammability limit in various ways, particularly the geometry of the environment in which ignition is observed, the flash point is, nevertheless, a flammability limit measurement. The flash point is readily shown to be the liquid temperature which produces a vapor pressure such that the resulting vapor-air mixture is just above the flammability limit. The flash point is thus a measure of the lean limit.

In a hazard analysis, some ambiguity occurs due to the changing vapor pressure with the fraction evaporated. If the vapor-to-liquid volume is less than that of the flash point test, a flammable mixture might occur at a lower temperature than indicated by the test, and if the vapor-to-liquid volume is greater, a higher temperature might be required than the flash point indicates. Aging (evaporation) of a fuel also tends to raise the flash point. The first factor could lead to an unsafe condition while the other factors tend to be conservative. The only disadvantage is that the conservative estimate may lead to undue design difficulties which could be obviated if the actual conditions were known.

3.2.2.2 Fire Point

The fire point, closely related to the flash point and measured in the same type of equipment, requires that the material continue to burn, once ignited. The fire point occurs at a higher temperature than the flash point. It differs primarily in the fact that the fuel at its controlled temperature with heat transferred from the flame, must supply fuel vapor as fast as the vapor is consumed by the flame. The rate of vapor evolution is involved in the fire point measurement and not in the flash point measurement.

3.2.2.3 Volatility Effects on Thermal Ignition

An examination of typical AIT data easily shows that there is an apparent volatility effect for hydrocarbons with otherwise similar combustion properties. Examination of the mechanism of hot surface ignition readily offers an explanation for this tendency for higher volatility fuels to display a higher surface ignition temperature. It is possible that a volatile fuel generates mixtures which are very rich near the surface where the temperature is high while the favorable mixtures occur where the gas temperature is low. Since flow over the surface affects both the composition and temperature profile, not necessarily in similar patterns, much of the complex behavior of ignition temperature data is probably related to this effect of volatility. Since a distillation occurs with mixed fuels, the process becomes even more complicated. An example of the relation between boiling point and AIT is given in Figure 3.7.1.

3.2.2.4 Volatility Effects on Flame Inhibition

The use of halogenated hydrocarbons and other volatile materials to inhibit gas phase flame propagation also depends on the volatility behavior of the fuel. and, depending on the system involved, the relative volatility of the fuel and inhibitor. Obviously, the inhibitor must produce the proper gas phase composition. When the inhibitor is dissolved in the flammable fluid, the relative volatility becomes critical since the gas phase composition is determined by the distillation process. In most cases, it is possible to predict the effect of the distillation process on flash point. An anomaly can also exist under certain conditions. In some cases, as the liquid and inhibitor evaporate, the vapor composition is not flammable primarily because it is too rich to burn. As this mixture is diluted by air, it becomes flammable. In flash point experiments, this phenomenon exhibits itself as a flash outside of the cup and not within the confined vapor space. In a strict interpretation of the flash point experiment, this mixture would not be considered as having flashed, although a fire could certainly be initiated in the diluted (by air) vapor.

3.2.3 Compilation of Volatility Related Data of Typical Liquid Combustibles

3.2.3.1 Distillation Curves

Three sample distillation curves are given in Figure 3.7.2.[1]

3.2.3.2 Fuel Properties

Some fuel properties are listed in Table 3.2.

TABLE 3.2

Fuel Properties

Distillation (°C/°F)	Typical JET B	Typical JET A-1	Typical JP-5
Initial Boiling Point	60/140	168/335	182/360
End Point	235/455	266/510	260/500
Specific Gravity (°API)	.76/54.4	.81/42.3	.80/44.3
Freeze Point (°C/°F)	-62/-80	-50/-58	-49/-56
Flash Point (°C/°F)	-27/-20	38/100 min	60/140 min
Aromatics	11.4	16	16
Olefins	1	1	1
Viscosity, meter^2/sec (Centistokes @ -34°C/-30°F)	2.4×10^{-6}/2.4	9.2×10^{-6}/9.2	10.4×10^{-6}/10.4
Reid Vapor Pressure Pascal/psi, 38°C/100°F	17.9×10^{3}/2.6	$.69\times10^{3}$/0.1	$.69\times10^{3}$/0.1
Density (kilogram/l; lbs/gal)	0.767; 6.41	0.811; 6.78	0.814; 6.81

3.2.3.3 Hydraulic Fluid Properties

Some typical data on current and proposed hydraulic fluids are presented in Table 3.3.

3.2.3.4 Combustion Data of Aircraft Fluids

Some representative data on aircraft fuel and oil combustion properties are given in Table 3.4.

3.2.3.5 Flammability Limits

The flammability limits or flash point is a function of altitude as shown in Figure 3.7.3 for several representative fuels.

3.2.4 Spontaneous Ignition of Aircraft Fluids

The hazard of thermal or spontaneous ignition of fuels, hydraulic fluids, and lubricating oils by contact with hot surfaces such as engines and hot ducts is present in aircraft.[2,3] There is also the risk of ignition from hot gas leaks in jet efflux pipes and hot ducts. Although ignition of hydraulic fluids and lubricants can occur and lead to severe fires, fuel fires are more frequent and more serious due to the large amounts of fuel carried, to its flammable characteristics, and its less robust form of containment. This section summarizes the results of work done over a number of years on thermal ignition of fuels and hydraulic fluids.

The spontaneous ignition temperature (SIT) is not purely a function of the fuel composition, but is strongly dependent on the environment. The most favorable condition for ignition by hot surfaces exists in the uniformly heated enclosure (ignition associated with the wicking action of insulation).[4] However, this isothermal situation is unlikely to exist in practice. It nevertheless forms a basis for assessing the relative fire risk of fluids. In a non-uniformly heated environment, the surface temperature needed for ignition can be appreciably higher than that required in the isothermal vessel, and still higher with forced convection or ventilating flow. In such situations, the size of the hot surface and time taken to traverse it either by convective or forced flow are as important as the temperature.

The degree of risk in practical circumstances has been shown by past researchers[5,6] in this field to be most difficult to estimate from fundamental considerations owing to the complex nature of the chemical processes involved in the combustion of complex hydrocarbon fuels. It is essential to examine the thermal ignition of fuels in closely defined experimental conditions ranging from the most favorable for ignition to more representative environments where tests results are applicable to real aircraft situations. This has been done by a number of experimenters and a summary of the relevant studies is given below.

3.2.4.1 Ignition in Isothermal Vessels

Confined fuel-air mixtures at uniformly elevated temperatures are most conducive to thermal ignition. The heat loss, and consequently the risk of ignition, depends upon the distance of the reaction center from the vessel wall and the temperature difference. A degree of convection can occur within the vessel but the limited recirculation may have a cumulative effect resulting in longer ignition delay.

TABLE 3.3

Typical Hydraulic Fluid Properties

Property	Goal	MIL-H-5606	MIL-H-83282	Phosphate Ester	Navy MS 6 (Silicone)	Nonflammable Candidates MLO-76-122 Halocarbon Type	Nonflammable Candidates MLO-76-119 Freon Type
Viscosity							
@-87°C/-66°F	$\leq 2500\times10^{-4}m^2$/sec	2127	11,500	3500	2780	2518	3068
@-40°C/-40°F	$\leq$ 500m^2/sec	500	2200	600	908	524	501
@135°C/275°F	$\geq$01.5m^2/sec	3.4	2.3	2.5	6	1.4	1
Lubricity							
10kg	<0.5		.25	.41			.34
40kg	$\leq$1.0	.85	.48	.68	.82	.87	.60
Specific Gravity	$\leq$1.8	.83	.84	1.06	1.04	1.8	1.84
Vapor Pressure @121°C/250°F	1.33×10^4 Pascal $\leq$100 mmHg	19	.35			20	7.5
Pour Point °C/°F	$\leq$-59.5 $\leq$-75	-62 -80	-59.5 -75	-62 -80		Pass	Pass
Bulk Modulus Isothermal Secant @ 43°C/110°F	$\geq 1.4\times10^9$ Pascal $\geq$200,000 psi	1.4×10^9 200,000	1.6×10^9 230,000	1.9×10^9 270,000	1.0×10^9 152,000	1.2×10^9 169,000	
Flammability Heat of Combustion	1.6×10^7 j/Kg $\leq$5000 BTU/lb	4.2×10^7 18,100	4.1×10^7 17,700	2.9×10^7 12,800	2.26×10^7 9740	$.554\times10^7$ 2390	$.41\times10^7$ 1780
Auto Ignition Temperature °C/°F	$\geq$704 $\geq$1300	225 437	347 656	510 960	410 770	632 1170	671 1240
Hot Manifold Ignition Stream, °C/°F	$\geq$927 $\geq$1700	704 1300	427 800	760 1400	482 900	927 1700	$\geq$927 $\geq$1700
Spray, °C/°F	$\geq$927 $\geq$1700	760 1400	704 1300	816 1500	538 1000	$\geq$927 $\geq$1700	$\geq$927 $\geq$1700
Atomized Spray with Open Flame	Nonreactive	Sustains	Sustains	Extinguishes	Extinguishes	Nonreactive	Nonreactive

TABLE 3.4

Propulsion Compartment

Properties of Turbine Fuels, Hydraulic Fluids and Engine Oils

Fluid	Flash Point °C/°F	SpGr $H_2O=1$	Min. AIT in Air, °F/°C	Typical Net Heat Of Combustion j/kg BTU/lb	Hot Manifold Ignition Temp. in Air °C/°F		F/A Combustion Range, Mass Basis
					Stream	Spray	
Jet B (JP-4) Fuel	<-18/<0	0.78	229/445	4.35×10^7 18.710	704/1300	-	0.035-0.28
Jet A Fuel	41/105 min.	0.8	224/435	4.32×10^7 18,590	649/1200	-	0.035-0.28
JP-5 Fuel	60/140 min.	0.83	224/435	$4.32/10^7$ 18,440	704/1300	-	0.035-0.28
MIL-H-5606 Hydraulic Fluid (Mineral Oil)	91/195 min.	0.9	225/437	4.29×10^7 18,100	704/1300	704/1300	-
MIL-H-83282 Hydraulic Fluid (Synthetic Hydrocarbon)	221/430	-	347/656	4.13×10^7 17,700	427/800	704/1300	-
Skydrol 500B Hydraulic Fluid (Phosphate Ester)	182/360	-	510/950	2.97×10^7 12,800	760/1400	816/1500	-
MIL-L-7808 Engine Oil (Sebacate-Adipate Diester)	225/437	-	390/735	3.58×10^7 15,400	704/1300	816/1500	-
MIL-L-23699 Engine Oil	-	-	413/775	3.40×10^7 14,650	593/1100	816/1500	-

The following characteristics are considered to be among the main influences on ignition: temperature, pressure, type of fuel, fuel-air concentration, and size of enclosure. Associated with all these parameters is the "dwell time" between introduction of a mixture and the ignition. The effects of some of these conditions are indicated below.

3.2.4.1.1 Enclosure Dimensions

A number of studies[7,8] of the affect of vessel size indicate that the ignition temperature of kerosene and similar hydrocarbon vapors does not decrease appreciably in vessels of 0.5 m diameter sphere and larger. The effect of vessel size is illustrated in Figure 3.7.4.

3.2.4.1.2 Initial Pressure

Since aircraft operate over a range of pressures appropriate to the flight profile, studies have been made to establish its affect on ignition temperature as illustrated in Figure 3.7.4. Thermal ignition can occur at low pressures; however, the combustion pressure rise at altitudes above 30,000 ft. may well be contained within the fuel tank structure.

For work at pressures greater than atmospheric, references should be made to experimental data.[9,10,11,12,13]

3.2.4.1.3 Fuel Concentration

Experimental work[14,15] has shown that a much wider range of fuel concentration can be ignited thermally than in spark ignition. This is illustrated in Figure 3.7.5. It is clear from these results that the normal standards associated with the rich and weak limits associated with spark ignition do not apply to spontaneous ignition.

3.2.4.1.4 Ignition Delay

An important parameter in the study of ignition is the time between the introduction of the fuel and resulting ignition as illustrated in Figure 3.7.6. These delay times are important in assessing safety when convection flow and forced ventilation are available.

3.2.4.1.5 Ignition Characteristics of Fluids

Reports[14,16] deal with the ignition characteristics of a number of fluids covering minimum ignition temperature and the severity of the pressure rise. A summary of some of this information is given in Tables 3.5 and 3.6.

3.2.4.1.6 Ignition in Non-Uniform Temperature, Semi-Static Situation[14,16,17]

In practical situations, hot zones are rarely of uniform temperature. The minimum SIT data obtained in a uniformly heated enclosure may be a useful comparator for fuels and other fluids, but in general is too pessimistic for practical purposes. Work done using hot pipes within the temperature controlled sphere may more closely approximate the real conditions in which convective flow may predominate.

3.2.4.2 Pipe Ignition in Enclosed Environment

The sea level characteristics of various fuels are shown in Figures 3.7.7 and 3.7.8 for liquid and vapor, respectively, as ignition thresholds based upon the concentration for minimum ignition temperature. These results indicate that the enclosure temperature has a significant affect on the pipe ignition temperature and that for environmental temperatures up to 200°C, the pipe ignition temperature is still significantly above the minimum obtained in the enclosure tests described above.

3.2.4.2.1 Fuel Concentration

At the lower ignition temperature, very rich fuel concentrations, often of the order of 3:1 by weight, were required for ignition and only a narrow range of mixtures was ignitable - a result similar to that indicated for the enclosure tests (see above). At higher temperatures, this range broadens considerably both to the richer and weaker limits.

3.2.4.2.2 Pressure/Altitude

Most of the SIT studies have been at sea level pressure conditions. The work described in reference 6 showed that at high altitudes, the SIT's were higher and pressure rises smaller than at ground level. Figure 3.7.9 illustrates the effect of reduced pressure on ignition by a 76 mm diameter pipe and shows a significant rise in ignition temperature at altitudes about 15,000 ft.

3.2.4.2.3 Ignition Delay

The ignition delay[18] in a non-uniform temperature situation varies considerably with pipe size and fuel quantity. A typical plot for a 76 mm pipe is shown in Figure 3.7.10. The significance of the delay in these circumstances lies in the possibility of applying forced convection or ventilating air to sweep the mixture clear in the preignition phase and thereby prevent fire initiation in practical situations.

3.2.4.3 Other Non-Uniform Temperature Conditions

3.2.4.3.1 Hot Gas Ignition

A risk of ignition may occur when hot gases impinge on liquid or gaseous fuels. Work by Kuchta[17] indicates that for ignition gas temperatures much in excess of those for hot enclosures are required. The ignition temperature depends significantly upon the gas jet diameter. Evidence of hot gas ignition is indicated in reference 2.

3.2.4.3.2 Hot Flat Surfaces

Much work[19,20] has been done on ignition of fuels by hot flat surfaces. The work[20] on small hot surfaces using methane gas gives ignition temperatures well above that obtained in isothermal enclosures.[14] Work on larger hot surfaces gives ignition temperatures comparable with the largest pipe tested[14] (see Figures 3.7.8 and 3.7.9).

3.2.4.4 Practical Application and Extrapolation of Data

The hot pipe rig[14] is essentially a convective situation within an enclosed finite region and therefore may be considered a more severe condition than is often met in practice. For example, in a more open environment, the possibility of recirculation of the active species in the hot zone is low; thus a reduced risk of ignition. Forced ventilation will give additional relief and its significance is discussed later. However, even in the severe recirculation conditions there is evidence of considerable relief from the uniform enclosure described and may therefore be considered a useful criterion for safety in design against hot surface ignition.

For larger hot surfaces, extrapolation of the curves shown in Figures 3.7.8 and 3.7.9 may be possible where the lines are approximately parallel to the x axis. However, for pipes smaller than 19 mm diameter, extrapolation is not likely to yield very accurate results. Work by Kuchta[17] using hot wires may be relevant and interpolation may be made but deduction would be of limited accuracy since experimental conditions were somewhat different.

TABLE 3.5

Ignition Characteristics of Aircraft Fuels (Sea Level Pressure)

Fuel	Min. spontaneous ignition temp. °C RAE 0.46 m diameter uniformly heated sphere: Liquid	Vapor	Flash Point °C		Mean Molecular Weight	Estimated Carbon Number
Avgas	280	270	-40	typical	102	7.3
Avtag	212	224	-20	typical	143	10
Avtur	216	208	38	Min. for Specification	177	12.5
Avcat	218	208	60	Min. for Specification	182	13
Diesc	227	224	66	Min. for Specification	212	15

TABLE 3.6

Data on Flammability of Hydraulic Fluids and Lubricating Oil

Fluid	Fluid Type	Minimum SIT °C 0.46 m Sphere	Minimum SIT °C ASTM Methods*	Flash Point** °C
DTD 585	Mineral oil	220 (liquid)	225	93
XRM 206 A	Synthetic hydrocarbon	247	340	204
Oronite M2	Silicate ester	270	404	210
Skydrol 500 A	Phosphate ester	285	593	200
Skydrol 500 C	Phosphate ester	310	482	200
MCS 4630	Organo phosphate	293	388	210
Silkodyne H	Chlorinated silicone	375	480	300
Hydraunycoil	Di-ester	270	400	210
Reolube Hyd 21	Phosphonate based fluid	256	-	-
Aerosafe 2300	Phosphate ester	276	405	185
Hijet III	Phosphate ester	286	528	171
OX-38 (lubricating oil)	Di-ester	271	-	216

*Two ASTM methods were available; where both tests were made, the test giving the minimum value has been chosen.
**Generally extracted from firm's technical brochure.

3.2.4.5 Spontaneous Ignition in Flow Systems - Tunnels

Experimental work has been done by Goodall and Ingle[19] on ignition of flammable fluids by hot surfaces including the relatively static to the flow situation in a short tunnel. The static tests involving parallel hot plates are essentially an extension of the study with hot pipes as summarized earlier, and confirms the increased temperatures required for ignition compared with the isothermal tests.

More recently, work has been done in longer tunnels (.8 m[21] and 6.2 m[22]), thus giving greater "dwell" times to the mixture at the appropriate temperature in its traverse through the tunnel and thereby covering conditions more relevant to current aircraft situations.

The work[21] involved a study of a number of conditions such as the affect of heated floor length, floor obstructions, fuel and air temperatures, pressure, heat shields, and ignition flash back. Selected aspects of these experiments using aviation kerosene fuel are discussed briefly in the following paragraphs.

3.2.4.5.1 Effect of Heated Floor Length

The results are not conclusive, but generally indicate that air velocity must increase as heated surface becomes longer (Figure 3.7.11). Since ignition in the static situation has usually a well-defined "dwell" time (see Figure 3.7.6), it would be expected that the tunnel air velocity would be a significant factor in ignition. However, in the dynamic situation, boundary layer characteristics could be important in both the laminar and turbulent flow conditions.

3.2.4.5.2 Floor Obstructions

An illustration of the affect of obstructions is given in Figure 3.7.12. There is no direct relationship between obstruction height and safe velocity. When the obstruction represents a significant restriction in the tunnel, the air velocity required is less than for the smaller obstructions at temperatures above 450°C. However, increasing the mixture velocity to a value above the worst threshold conditon should enable higher operating temperatures to be obtained with safety for all situations.

3.2.4.5.3 Effect of Fuel and Air Temperatures

Increasing the fuel or air temperatures reduces the surface temperature for ignition or alternatively demands an increased air flow for safety as illustrated in Figures 3.7.13 and 3.7.14.

3.2.4.5.4 Pressure Effects

An increase in air pressure within the tunnel reduces the floor temperature at which ignition can occur or alternatively raises the velocity required to prevent ignition. Low air pressures appropriate to altitude conditions permits higher surface temperatures for ignition (see Figure 3.7.15).

3.2.4.5.5 Floor Heatshields

The provision of a simple heat shield above the heated surface generally results in a safer situation than with the exposed floor. This situation arises in the shielding of jet pipes and hot ducts.

3.2.4.5.6 Flashback Ignition

Studies[21] of flashback ignition have covered a number of parameters and thereby enabled threshold conditions to be established to prevent flashback in flowing mixtures.

3.2.4.6 Summary and Conclusions

A considerable amount of applied research has been done on the spontaneous ignition of aircraft flammable fluids such that it is possible to make a viable estimate of the risk of ignition in most situations and to devise methods to remove or reduce the risk.

Testing of fluids in the essentially static situation such as an enclosure of optimum size serves as a useful tool for classifying fluids as to their relative ignitability. However, the results are not adequate when applied to the types of environment found in aircraft as indicated below.

When situations arise in which free convection or restricted convection is present, then ignition temperatures are much higher than in the isothermal enclosures. The ignition risk for particular fluids are, however, dependent on hot surface size. Tests indicate a 150 mm diameter (6") pipe approaches an ignition temperature similar to the flat plate.

In conditions where forced ventilation is applied, higher surface temperatures may be used with safety. Less ventilating air is required if the air and fuel temperatures are kept low.

In designing for safety, consideration must be given to all the parameters involved, such as fuel and air flow temperatures, size or length of hot surfaces, obstructions, environmental temperatures, air pressure, and insulation effects. In general, the temperature of all surfaces on which flammable fluids may impinge should be as low as possible and preferably less than 240°C unless alleviating factors such as those described are applicable. Above 240°C, a complete assessment of each situation should be made.

3.2.5 Spark Ignition of Aircraft Fluids

The only fluid of major concern in which ignition can be initiated by a spark in the aircraft situation, is the fuel. The ignition of less volatile materials such as hydraulic fluids and lubricating oil would in all probability result from thermal ignition. In addition to ignition by electric sparks, ignition by frictional sparks will be discussed considering these as point sources of energy.

The subject will be covered in two main sections. (1) Minimum ignition energy requirements for hydrocarbons under various conditions. (2) Sources of sparks that can be encountered in aircraft operations and accident situations.

3.2.5.1 Spark Ignition Energy Requirement for Hydrocarbons (Laboratory Data)

The spark ignition of a flammable fuel-air mixture requires a spark of a certain energy (E_i min.) is defined as the minimum electrical energy stored in an electric circuit at the initiation of the weakest spark capable of igniting a flammable mixture. The E_i minimum values for several hydrocarbons were measured by von Elbe and co-workers[23-26] and were found to be of the order of approximately 0.2 mJ under ideal conditions. Similar E_i minimum values have been measured by other workers and Table 3.7 taken from reference 27 compares the results obtained by four researchers.

TABLE 3.7

Comparison of E_i Minimum Values Reported by Various Workers

Hydrocarbon	Ignition Energies (mJ) Moorhouse et al[27]	Lewis & von Elbe[23]	Metzler [28,29]	Calcote et al[30]
Methane	0.63	0.29	--	--
Ethane	0.41	0.25	--	--
Propane	0.46	0.25	--	0.26
n-Butane	--	0.26	--	--
n-Pentane	0.5	--	0.27	0.29
2-Pentane	0.7	0.23	0.24	--
n-Hexane	0.7	--	0.30	--
1-Hexane	0.6	--	--	--
n-Heptane	0.7	0.24	0.29	--

Moorhouse, et al attribute their higher results to the fact that they are based on an ignition probability of 0.8, whereas the other data has an ignition probability of 0.01.

3.2.5.2 Parameters Affecting E_i Minimum

The actual E_i levels required to ignite a flammable mixture may be much higher than the E_i minimum values presented in Table 3.7 depending on the influence of several parameters. The most significant parameters in the context of the present discussion are: (1) hydrocarbon concentration, (2) hydrocarbon composition, (3) oxygen concentration, (4) mixture velocity, (5) pressure and temperature, and (6) electrode configuration. These parameters will be discussed separately.

3.2.5.2.1 Hydrocarbon Concentration

The energy required to ignite a flammable hydrocarbon-air mixture is dependent upon the hydrocarbon concentration; E_i minimum normally occurring above the stoichiometric point. A marked increase in energy is required on either side of the E_i minimum point. This is illustrated in Figure 3.7.16 taken from Reference 31 where it can be seen that the E_i level increases near the flammability limits by approximately two orders of magnitude above the Ei minimum value. Although E_i minimum normally occurs at a point on the rich side of the stoichiometric point, Figure 3.7.16 shows that methane is an exception from other members of the alkane series.

3.2.5.2.2 Hydrocarbon Composition

The E_i minimum requirements for ignition of hydrocarbons in an homologous series are approximately the same being independent of carbon number. The E_i minimum point, however, occurs at higher equivalence ratios as the homologous series is ascended. This is illustrated in Table 3.8.

TABLE 3.8

Equivalence Ratios for E_i Minimum of the Alkanes

Alkane	% Alkane at E_i Min.	Equivalence Ratio
Methane	8.45	0.89
Ethane	6.61	1.17
Propane	5.07	1.26
n-Butane	4.53	1.42
n-Pentane	4.00	1.56
n-Hexane	3.64	1.69
n-Heptane	3.36	1.80

3.2.5.2.3 Oxygen Concentration

With an increase in the atmospheric oxygen content above the normal 21%, there is a marked reduction in the energy requirement for the ignition of a hydrocarbon vapor (see Figure 3.7.17). The E_i minimum point also shifts towards higher hydrocarbon concentrations with increased oxygen content. The affect on E_i is therefore more likely to be encountered with more volatile fuels that exist predominantly in the rich condition under conditions of operation.

The oxygen content of a fuel tank or vent system atmosphere can increase as the result of the release of oxygen enriched air from fuel that is

supersaturated with air. Such a release can be produced by violent agitation of the fuel or reduction in pressure. Laboratory scale tests at simulated altitudes have shown an oxygen enrichment to 35% by volume to be possible.[32]

3.2.5.2.4 Mixture Velocity

The effect of mixture velocity on E_i was studied by Swett[33] who reported that E_i increases linearly with mixture velocity. More recent work by Ballal and Lefebvre[34] showed that, although mixture velocity has an adverse effect on E_i, the effect is not as great or linear, as reported by Swett. The affect of velocity on E_i is illustrated in Figure 3.7.18, which is taken from Reference 34. This figure shows that under the conditions of the test and at an equivalence ratio of 1.5, E_i minimum increases from about 3 mJ under static conditions to 15 mJ at a flow of 6m/s with a smaller increase to about 18 mJ at 15m/s. The adverse effect of velocity on E_i minimum is attributed by Ballal and Lefebvre to dilution of the spark kernal in its initial period of development by cold mixture requiring more energy to compensate for loss of heat. This is compensated somewhat by the displacement of the spark downstream by the flowing mixture, reducing the loss of heat and active radicals to the electrode. This compensation is considered more significant with an arc discharge as opposed to a glow discharge and may explain why E_i minimum values reported by Swett show more dependence on velocity since a glow discharge was used in his work. Ballal and Lefebvre also showed that E_i minimum increases with increase in turbulence intensity.

3.2.5.2.5 Temperature and Pressure

The relationship between E_i minimum and pressure can be expressed as follows:

$$E_i \text{ min } \alpha \frac{1}{\rho^X}$$

A value of X = 1.76 was determined by Metzler[28] and in later work[29] he reported a value of about 1.82 ranging from 1.65 to 2.00. The relationship between E_i minimum and pressure is illustrated in Figure 3.7.19 taken from Reference 29.

The relationship between E_i minimum and temperature can be expressed as follows:

$$E_i \text{ min } \alpha \frac{1}{T^Y}$$

Values of y = 2.03 were reported by Moorhouse.[27]

A combined expression can be used to cover both parameters.

$$E_i \text{ min} = KP^{-X}T^{-Y}$$

3.2.5.2.6 Electrode Configuration

The affect of electrode shape and spacing is discussed in some detail in Reference 35, where it is shown that these parameters are of considerable significance. From the point of view of accidental ignition by the fracture of electric power lines, as might be encountered in an aircraft incident, the definition of these parameters is indeterminate.

3.2.5.3 Spark Ignition of Fuel Sprays and Foams

Discussion so far has concerned the ignition of gases or vapors; a special case exists for the ignition of fuel sprays and foams which can form flammable mixtures.

The E_i requirement for the ignition of sprays and foams will be greater than for vapor because part of the energy is dissipated in shearing the fuel droplets. The minimum energy required to ignite a fuel spray decreases with increasing temperature and with increasing fuel volatiliy. Liebman, et al[36] studied the ignition of fuel sprays and the relation between E_i minimum and temperature for three fuels shown in Figure 3.7.20. The E_i minimum for ignition of a kerosene spray is shown to be approximately two orders of magnitude greater than that for a vapor.

The energy to ignite flowing kerosene-air mixtures was studied by Lefebvre, et al[37] who demonstrated the strong influence of spray droplet size on ignition energy requirements. This is illustrated in Figure 3.7.21. It was also shown that the ignition of larger droplet sizes cannot be accomplished any more easily by using increased energy.

The ignition of kerosene foams were studied by Kester, et al[38] who reported that an ignition energy of 24 mJ was required at the foam-air surface and 39 J in the bulk foam. No ignition was possible at the foam-fuel interface with energies up to 50-60 J.

3.2.5.4 E_i Minimum Requirements in Aircraft Operations

The affect of practical conditions, as experienced in aircraft operations on E_i minimum can be summarized as follows:

(1) E_i minimum for hydrocarbons is recorded normally when the equivalence ratio is greater than unity. Therefore, fuels which are more frequently present on the rich side of the stoichiometric point, over the temperature range normally encountered in aircraft operations, would likely be ignited in an energy limited situation. However, as the rich limit is approached (and the lean limit), E_i could be greater than E_i minimum by two orders of magnitude.

(2) Due to the relationship between E_i and temperature and pressure, the energy required to ignite a flammable tank atmosphere at altitude could be greater by two orders of magnitude over that at atmospheric pressure and ambient temperature. This may be compensated somewhat by the reduction in energy required in an oxygen enriched atmosphere, a situation which may exist at altitude due to the preferential release of dissolved O_2 compared with N_2. This reduction is approximately one order of magnitude.

(3) The ignition of a flowing fuel-air mixture under turbulent conditions may be increased by approximately two orders of magnitude over stagnant conditions. A typical situation would be ignition in an aircraft vent system where again the presence of excess oxygen could have a compensating affect.

(4) Ignition of fuel sprays and foams such as might exist in an aircraft tank during flight or refueling will require an energy level several orders of magnitude greater than the energy required to ignite a gas or vapor under ideal conditions. The ignition of kerosene sprays requires an energy two orders of magnitude greater than that to ignite wide-cut fuel.

A spark ignition energy required to ignite a jet fuel either during normal aircraft operations or under conditions which exist in an accident situation is quite likely to exceed the fractions of a milliJoule recorded for the ignition of hydrocarbons under ideal laboratory conditions. An increased energy requirement to a level of two orders of magnitude would not be unusual. The second part of this report will, however, show that energies far in excess of these requirements are available for ignition in many phases of aircraft operations.

3.2.5.5 Sources of Sparks Encountered in Aircraft Operations

Spark sources encountered in aircraft operations and accident situations can be classified as: (1) Electrical sparks produced from AC or DC electric circuits of aircraft or support vehicles - "Circuit Electric Sparks". (2) Electrostatic sparks - produced by electrostatic charging in the fuel, on the aircraft skin, or by atmospheric electricity. (3) Frictional sparks -produced by abrasion of metal surfaces.

3.2.5.5.1 Circuit Electric Sparks

The energy level in almost all aircraft electrical systems is well above that to ignite fuel vapors and sprays. In recognizing this fact, aircraft are designed to minimize the possibility of ignition by equipment malfunction or in an accident situation. Wide-bodied commercial transports are designed to meet the requirements of MIL-STD-704 - "Characteristics and Utilization of Aircraft Electrical Power". All electrical circuitry is isolated from areas containing combustible fluid vapors by conduits and vapor barriers. Furthermore, all areas adjacent to electrical and containing combustible vapors are air purged to maintain fuel-air ratios below combustible limits. An exception to this is the fuel quantity gauging system which of necessity has to be within the fuel tanks. However, the energy available from this system is well below that required to ignite fuel vapors.

In an accident situation where aircraft break-up occurs, rupture of electric cables can take place providing high energy levels for ignition of flammable vapors and sprays. Typical energy sources available when JT3D engine separates from a DC-8-63 are as follows:

3.2.5.5.2 Electrical Sources of Ignition When Engine Separates From Aircraft on DC-8-63 Aircraft

1. Arcs occurring due to inductive surges when wires break.

Circuit	Energy (in Joules)	Remarks
C.S.D. Magnetic Trim Head	0.031	
C.S.D. Underspeed Sensor	0.0001	
C.S.D. Disconnect Solenoid	7.8 to 9.8	This circuit would normally be de-energizing so their would be no arc.

2. Arcs occurring due to dangling "live" cables contacting aircraft structure.

Circuit	Energy (in Joules)	Remarks
Generator System Feeders	16.7 Joules per 1/2 cycle 400 Hz supply (i.e., each 1/2 cycle has a duration of 1/800 sec.)	Arc current would be approximately 890 amps. These feeders would be "live" for only 5 to 7 seconds after engine separation.
Generator Failure Warning Light	0.960 Joules per second	
Engine Ignition	0.317 Joules per 1/2 cycle of 400 Hz supply	Arc would normally break within 1/2 cycle.
Engine Anti-icing	166.5 Joules per second	
Engine Jet Pump and Engine Compressor Valve Control	171.6 Joules per second	
Low Pressure Pneumatic Regulation and Control Valves	83.7 or 91.7 Joules per second	

NOTE: (a) Several of the above energy values are expressed in Joules per second. The actual energy dissipated would depend upon the time duration of the arc. (b) The energy values expressed in Joules per 1/2 cycle of 400 Hz supply are the values to be obtained if the arc duration was a full 1/2 cycle. The arc normally breaks when the current goes through zero, and the arc duration would depend upon the portion of the half cycle remaining when the contact is broken.

To assist in keeping fuel away from electric spark ignition sources in an accident, fuel lines in the DC-10 fuselage are kept away from electric power lines and are made of one piece resilient steel with minimum connections, enclosed by an outer drained aluminum tube. This is attached by nylon clamps below the floor structure so that differential displacement of the structural members will not sheer the fuel line. Fuel lines are routed within fuel tanks as much as possible.[39]

In addition to the electric energy available in the aircraft there are several other electric energy sources in the servicing and support vehicles that frequently surround an aircraft on the ground. These vehicles have high tension ignition systems with typical energies in the order of 40-80 mJ. Poorly maintained ignition systems could produce external sparks which might produce ignition if a fuel spill occurs.

In addition, ground power units and air-conditioning units have 110V and 220V systems that frequently require electric power cables across the tarmac, these can become abraded providing potential ignition sources.

3.2.5.5.3 Electrostatic Charges

Electrostatic charges capable of producing electric sparks can be generated during aircraft operations in the following manner: (a) Generation within the fuel during fueling, (b) Generation on aircraft and support vehicles by friction (included in this classification would be charge generation on personnel clothing). (c) Atmospheric electricity.

3.2.5.5.3.1 Electrostatic Charge Generation During Fueling

During the flow of a hydrocarbon type fuel through pipes, valves, filters, etc., an electrostatic charge can be generated in the fuel which, if not able to relax sufficiently fast, can allow the accumulation of hazardous potential levels inside a receiving tank. Although pure hydrocarbons are virtually perfect insulators, commercial fuels contain trace quantities (parts per billion) of electro-kinetically active material which can impart a charging tendency to the fuel. The generation of static charge in the flowing fuel is attributed to the adsorption of one ionic species (either negative or positive ions) on pipe walls or the filter media. This adsorption leaves an electrical unbalance in the fuel with a predominance of unadsorbed ions acting as a streaming current. This is illustrated in Figure 3.7.22(a,b).[44]

The streaming current or the charge density can be measured using appropriate instrumentation and these properties are related as follows:[41]

$$i = Qv$$

where i = streaming current (μA).
Q = charge density ($\mu C/m^3$).
v = volumetric flow rate (m^3/sec).

The charge density is a function of the flow rate (v), the area (a), and characteristics (x) of the fuel surface interface where ionic separation is taking place.

$$Q - f(v,a,x)$$

x represents the charging tendency, an unpredictable factor depending upon the charging tendency of the fuel (type and quantity of ionic species) and the activity of the fuel surface interface.

The charge generated in the fuel will relax and the rate of charge relaxation is defined as follows:

$$Q_t = Q_o e^{-t/\tau}$$

where Q_t = charge density after t seconds ($\mu C/m^3$)
τ = relaxation time. The relaxation time, $\tau \quad \frac{\varepsilon\varepsilon_o}{k}$
where ε = absolute dielectric constant of vacuum

$$(8.854 \text{ A sec } v^{-1}\ m^{-1})$$

ε_o = relative dielectric constant ($\sim$2 for most hydrocarbons).
k = electric conductivity of fuel (picoSiemens/m).

The relaxation time is normally defined as the time required for the charge to relax to 36.8% of its original value.

$$\text{i.e. } \frac{Q_t}{Q_o} = 0.368 = e^{-1}$$

The relaxation time is dependent upon conductivity and values for various conductivities are shown in Table 3.9.

TABLE 3.9

τ Values for Various Conductivities

k(pS/m)	τ(sec)
0.01	1800
0.1	180
1.0	18
10	1.8
100	0.18

Most aviation fuels, not containing static dissipator additives, have conductivities around 1 pS/m. With the high refueling rates, there is little time provided downstream of the filter for charge to relax before it enters the aircraft tank. Depending upon the conductivity and relaxation volume, the

fuel will either relax its charge to the tank wall or the charge will accumulate on the fuel surface and eventually produce an electric discharge, if the breakdown voltage is exceeded. This is illustrated in Figure 3.7.22(b).

3.2.5.5.3.2 Static Incidents and Programs

Following several incidents involving fires and explosions during aircraft fueling,[42] several investigational programs were conducted (four typical programs are described in references 43, 44, and 45 to determine the significance of the electrostatic hazard. Salient points from these programs were: (1) The prime charge generator in a fueling system is the filter water separator used to remove dirt and water from the fuel. A combination of filter water separator and a filter type contamination monitor was found to produce excessive charging with charge densities over 1,000 $\mu C/m^3$ being recorded.[45] (2) Charge densities in excess of 400 $\mu C/m^3$ were often recorded associated with the recording of high field strengths in receiving tanks. (3) Charge generation increased with flow rate. (4) Electric discharges were frequently detected inside tanks with energies far in excess of the theoretical E_i minimum values. Energies of several milliJoules were reported in reference 44. (5) The effectiveness of a static dissipator additive in reducing the hazards of charge generation was demonstrated.[45]

Incidents related to electrostatic discharges in aircraft fuel tanks have continued to occur in those areas where a static dissipator additive has not been incorporated in the fuel.

Typical incidents include two explosions that occurred in 1970 while Boeing 727 aircraft were being refueled.[46] Recently, the U.S. Air Force has experienced explosions in foam filled bladder tanks of certain aircraft. As a result of these incidents, several investigational programs have been initiated.

3.2.5.5.3.3 Static Dissipator Additives

In 1962, following incidents involving Canadian military aircraft, it was decided to carry out flight tests using fuel containing a static dissipator additive. This additive functions by artificially increasing the fuel conductivity so that, although charge generation still takes place, the charge relaxation is so rapid that the hazardous accumulation of potential inside the receiving tank is prevented. As can be seen from Table 3.9, the relaxation time, with a conductivity of 100 pS/m is only 0.18 seconds, which means that even at high fueling rates the majority of the charge has relaxed by the time it leaves the filter separator housing.

3.2.5.5.3.4 Electrostatic Charges on Aircraft

During flight, electrostatic charges can be developed on aircraft skin by: (1) Contact with uncharged precipitation particles, smoke and dust which normally leave a negative charge on the aircraft - this is called precipitation static. (2) Flight through an electric field such as is generated between oppositely charged regions of cloud - this is called exogenous charging.

The charge on the aircraft can build up to levels sufficient for discharges to occur either by corona discharges from extremities or sparking across unbonded or poorly bonded sections. The discharges can produce electric interference and the possibility of ignition of fuels and electro-explosive devices is reported.[47] The ignition of fuel vapors inside a fuel tank (as opposed to vapor at the fuel tank vent) is, however, more likely to occur by lightning strikes because of their significantly higher energy levels. This is discussed in more detail later.

On landing, the aircraft may retain some of the charge generated during flight and can continue to become charged by wind blowing across the skin producing precipitation static. Before servicing the aircraft, the potential between the aircraft and the refueling vehicle has been equalized by bonding to prevent sparking. The bonding of aircraft and refueler is a mandatory operation for all refuelings. Additionally, grounding of the aircraft is considered to be an extra safety measure for protection against electrostatic charge and for stray electric currents, by some operators.

Helicopters are particularly prone to precipitation static due to violent agitation of dust, snow, or ice particles on the ground produced by the rotating blades. A classic example of an explosion produced by this mechanism is described in reference 48. Briefly, this incident involved transfer of a helicopter from a parking area to a fueling point some 900 meters away, hovering over snow covered ground with low atmospheric humidity. Attempts to refuel from a drum without previously bonding the hose nozzle produced a violent explosion as the nozzle contacted the filler neck. The helicopter was destroyed and fatalities would have occurred if anyone had been on board.

To combat electrostatic charge generation on clothing, refueling personnel are required to wear clothing which will produce low charge levels when brushed. This is normally accomplished by using non-synthetic fibers such as cotton and antistatic additives. The National Bureau of Standards report[49] that 50-50 cotton polyester blend generates less charge than 100% cotton. They also report that neither footwear nor ground surfaces of flight lines should have a resistance exceeding 10^9 ohms. Footwear with a resistance of less than 10^6 ohms may create a personnel shock hazard and the desired resistance range is therefore 10^6-10^9 ohms.

3.2.5.5.3.5 Atmospheric Electricity

Lightning strikes on aircraft are not an uncommon occurrence and normally take place at lower altitudes frequently on take-off or landing. The increase in the number of short haul flights in the past decade has increased the exposure of aircraft to the lightning environment. While the increase in the number of delays at overcrowded airports, causing aircraft to fly in low altitude holding patterns has had a similar effect. Military aircraft, because of the nature of their missions, may not be able to divert from thunderstorm activity and are, therefore, more prone to lightning strikes.

The most commonly quoted fatal accidents attributed to lightning induced ignition took place in 1959 and 1963. In June 1959, a Lockheed Constellation flying near Milan exploded at about 10,000 m during thunderstorm activity, and in 1963 a Boeing 707 flying near Elkton, Maryland, exploded at about 4,500 m under similar circumstances. The reports of both accidents[50,51] attributed their cause to lightning induced ignition of fuel at the aircraft vents. Although the majority of lightning strikes cause only minor damage unassociated with fuel ignition, statistics presented by the Royal Aircraft Establishment, Farnborough, UK, below show a surprisingly high number of explosions amongst strikes reported to RAF aircraft. However, no aircraft was lost as a result of these incidents.

Aircraft Type	Strikes	Explosions
Canberra (Wing Tanks)	19	3
Shackleton (Wing Tanks)	18	3
Jet Provost (Wing Tanks)	7	5
Lightning (Ventral Tanks)	2	1
	46	12

The high incidence of explosions to the Jet Provost wing tanks is attributed to their plastic construction - a vulnerability that has since been corrected.

3.2.5.5.3.6 Mechanism of Lightning Strikes

A cloud to ground lightning strike consists of three phases (cloud to cloud strikes, although not so well-understood, are considered to be similar although of lower energy). The initial or pre-strike phase occurs as a lightning step leader approaches an extremity of an aircraft initiating high stress streamers. When part of the stepped leader contacts a streamer, the aircraft becomes part of the lightning channel. Stepped leaders will then propagate from other extremities until one branch contacts the ground. Average charge in the whole stepped leader channel is about 5 coulombs. The return stroke starts immediately after completion of the stepped channel between cloud and ground and the high peak current phase occurs. Peak currents on the order of 10^4 to 10^5 amperes are produced, although only a small part of the total energy is transferred because its duration is measured in micro seconds. The secondary or continuing current phase follows the initial return strike with currents on the order of a few hundred amperes; although the current is lower, the duration is measured in tenths of a second (up to 1 second) and as a consequence the majority of charge, measured in hundreds of coulombs, is transferred in this phase.

The lightning channel remains reasonably stationary in space while transferring its charge. The contact point on the aircraft can remain stationary with the resultant high energy transfer allowing the high temperature generated to do structural damage. However, frequently the forward motion of the aircraft relative to the lightning channel allows the channel to sweep back over the aircraft. This is called the swept stroke phenomena. The nature of surface features at various locations on the aircraft skin can cause the channel to contact and remain at these points for different periods during the swept stroke. The longer the period the channel is stationary, the greater the amount of energy transferred. Aircraft surfaces are classified into three zones. Zone 1 describes areas of high probability for a direct strike; Zone 2 describes areas prone to swept stroke action; and Zone 3, all other areas. Lightning protection measures for different areas are dependent on Zone classification.

3.2.5.5.3.7 Explosion and Fire Hazards/Lightning

The ignition of fuel in an aircraft by lightning can be caused by several distinct mechanisms. These are discussed briefly.

3.2.5.5.3.8 Ignition by Sparking Across Poorly Bonded Structures

When an aircraft is struck by lightning, a pulse of high current flows through the aircraft from the entrance to the exit point. The amount of energy dissipated in the aircraft structure is minimized by providing a low resistance electrically well bonded structure. Poor bonding in areas in which fuel vapors may occur could result in sparks being produced across the poorly bonded junction of sufficient energy to ignite an explosive atmosphere. It is imperative, therefore, that design criteria include good electrical bonding. The use of non-metallic adhesive structural bonds warrants special attention for provision of adequate electrical bonding because of the possibility of carbonization of the adhesive by sparking resulting in a loss of structural integrity.[52]

3.2.5.5.3.9 Ignition by Burn Through of Fuel Tanks

At the attachment point of a lightning stroke to an aluminum aircraft surface, sufficient heat can be generated to cause local melting and burn through if the skin is of insufficient thickness. The burn through condition is more likely to occur with a direct as opposed to a swept stroke. If burn through occurs into an area containing fuel vapors, ignition can occur. The FAA recommendation for a minimum skin thickness of 2 mm is dictated by the most severe lightning damage, i.e., Zone 1 areas. The fuel tanks in commercial aircraft are located in Zone 2 areas, therefore, the 2 mm is considered conservative. Due to structural load requirements, skin thicknesses for integral tanks have been at least 2 mm and the use of this limit for lightning protection of current aircraft has not caused problems. For future aircraft where more advanced lightweight materials and composite materials are being considered, a re-evaluation of this requirement may be necessary. A procedure for determining the lightning strike performance of metal skins has been proposed by Oh, et al.[53] A curve showing ignition threshold data versus dwell time is produced which will indicate whether or not a specific panel is prone to lightning ignition of backside fuel vapors. Such evaluation procedures are necessary for some of the advanced composite materials which are either non-conducting or of low conductivity. Non-conducting materials which are either non-conducting or of low conductivity. Non-conducting materials such as fiber reinforced plastics can be punctured by the lowest energy direct or swept strokes. The ignition of fuel vapors by lightning strokes through aircraft skins was studies by Kester, et al.[38] The investigation was not limited to ignition by burn through and the possibility of lightning producing a localized high temperature spot on the undersurface of the skin, of sufficient duration to exceed the ignition delay, was also studied. At 660°C, the melting point of aluminum, the ignition delay is approximately 30 seconds and because of the metal's high thermal conductivity, it would be impossible for a hot spot to maintain that temperature for that period of time. Hot spot ignition has not been a problem with aluminum and in the referenced investigation, all cases of ignition with aluminum were due to burn through. Titanium and stainless steel, however, have relatively low thermal conductivities and high melting points, and the investigation showed that hot spot ignition with those metals was possible. Hot spot ignition temperature for ignition of a propane-air mixture was found to be about 1315°C, although this may depend on the spot size. The use of titanium and stainless steel, or other high melting point, low thermal conductivity, alloys in advanced aircraft structures would require adequate skin thicknesses to avoid hot spot ignition.

3.2.5.5.3.10 Ignition of Vapor at the Fuel Vent System Exit

Several investigators have shown that ignition of fuel vapors at an aircraft vent exit can, under certain conditions, result in flame propagation through the vent system. The flammable envelope at the vent exit has been found to be quite limited in size[54] and Brenneman[55] observed a slightly larger envelope for wide-cut fuel compared with kerosene. Other factors influencing the probability of ignition include vapor-air velocity in the vent system (the higher the velocity, the less chance of ignition and propagation), and the airstream velocity over the exit. Staham,[56] using simulated lightning strokes at the vent, found that the probability of ignition was reduced 100% under static conditions to 3% with an air flow of up to 170 kmph. Following the Elktron accident, modifications were made to the 707 aircraft to provide improved bonding and a metal overlay at the vent surge tank to reduce the possibility of lightning penetration. Fire suppression devices were also fitted to the vent system of the 707 and other related aircraft.[57]

Recommendations for vent system design include keeping the vent exits away from Zone 1 areas if possible. Protective methods such as flush or recessed vent exits or diverter rods are also recommended. Stahman[56] found that with a recessed vent exit, ignition could not be produced by streaming from the wing tips produced by application of 5 x 10^6 volts, typical of the pre-strike phase of a lightning stroke.

3.2.5.6 Friction Sparks

Friction sparks are hot or burning metal particles abraded when two metals or a metal and another surface are scraped together under high bearing loads. The formation of such sparks could be expected in an aircraft crash situation. The ability of these sparks to ignite a fuel in a crash situation is dependent upon: (1) Nature of materials producing the spark (normally the harder the materials, the greater the chance of producing an incendive spark, (2) Bearing pressure, and (3) Slide speed.

It is known from experimental crashes that abraded steel particles can ignite gasoline and that under the conditions used in these crashes, aluminum did not produce igntion. Campbell[58] studied the friction spark ignition characteristics of aluminum, titanium, magnesium, chromium-molybdenum steel, and stainless steel by dragging samples across asphalt and concrete runways in the presence of gasoline, wide-cut fuel and kerosene. In summary, it was found that: (1) Aluminum did not produce ignition at bearing pressures up to 10,000 kPa and sliding speeds up to 64 kmph. (2) Titanium, magnesium, chrome-molybdenum steel, and stainless steel produced friction sparks that caused ignition at sliding speeds and bearing pressures well below those that could be expected to a crash. Titanium produced the most sparks. (3) The ignition of magnesium particles does not require much energy because its ignition temperature is relatively low. Once ignited, however, the burning particles become a powerful ignition source with a theoretical flame temperature of approximately 5,500°C. (4) Fuels of low volatility may be slightly safer with respect to friction spark ignitions.

There are several sources of sparks, both electrical and frictional, in aircraft operation or produced as a result of an accident, which have energies far in excess of the minimum ignition energy for aviation fuels.

3.3 Aircraft Interior Materials

The research toward improving safety in flight of military and commercial aircraft, and even more specifically, the safety in case of a cabin fire, depends upon the evaluation of the materials used in the construction of the aircraft cabin.

Much has been said and written on the flammability of aircraft cabin materials as well as their tendency to emit smoke.[59-65] The regulations concerning flammability are applied strictly, and as a result, it is normal to have investigations in official agencies and industry.

With respect to the toxicity of the gases emitted by combustion or pyrolysis, the problem is so complex that it is not likely to see the application of regulations for a number of years. The work on this problem has been extensive: we survey the state-of-the-art in the first part of this section of the report while the second part will be devoted to full-scale and sub-scale studies.

3.3.1 Status of the Laboratory Work Concerning the Toxicity of Gas from the Pyrolysis and Combustion of the Materials used in Aircraft Cabins

One of the major hazards to which a passenger is exposed in an aircraft in the face of a cabin fire is the toxicity of the gases emitted by the combustion of the materials which often occur well in advance of the fire. In recent years, research workers have expended a large effort directed toward making model fires and analyzing the gas emitted. The FAA, with the team of Spurgeon-Speetel and Feher, have studied the thermal decomposition of 75 materials in a combustion furnace held at 600°C for 5 minutes under a flow of 2 l/min. The concentrations of HCL-HCN-H_2S-HBr-HCOH have been determined by differential impulse polarography. NO_2 and SO_2 by visible spectrophotometry, HF by potentiometry, and CO by I.R. absorption.

The results obtained show: (1) Cotton/rayon fabric rank as the maximum emitters of CO among the fabrics. (2) Wool, when burning, gives off H_2S along with other gases. (3) The fabrics coated with PVC rank high in the evolution of CO and HCl. (4) The polycarbonates rank high in the evolution of CO among the thermoplastics. (5) PMMA, fireproofed (FR), gives four times as much CO as non-fireproofed PMMA.

One can state that the fraction of the mass evolved during the first minute represents 85% of the total mass evolved in about 5 minutes. H_2S is emitted before the first minute while HCN and CO have parallel curves of evolution.

The evolution of CO-H_2S-HCN decreases with increasing ventilation.

Another very active team composed of Kourtides-Parker-Hilado (NASA and San Francisco University) has studied the combustion behavior and relative toxicity of presently used composite panels and future panels.[66]

State-of-the-art panels: laminated phenolic and acoustical polyamide honeycombs of various densities; laminated epoxy aromatic polyamide honeycombs.

The laminated bismaleimide panels which contain the carbon microballons are more resistant to fire. Those which contain quinone dioxime foam give good results.

The composites with epoxy give the most abundant smoke. The relative toxicity of the product with microballons is lower.

NASA[67] with Kourtides-Parker-Gilwee has initiated work on a thermochemical comparison between present day materials and those of the future.

PVF, much used in decorative films, begins to decompose at about 250°C.

The composite panels formed of films of polycarbonate phenolphthalein on laminated bismaleimide - honeycombs aromatic polyamide containing a polyquinoxaline foam give a very small proportion of smoke, with an LOI > 35 and a large proportion of ash which inhibits the combustion of the rest of the material.

Still using the same team of NASA, they developed a point of view which considered that the flammability and thermal protection offered by these materials was a function of their molecular structure and their thermochemical properties; they established a fire hazard curve to rate combustible materials: around 1.5 kg of combustible suffice to cause a fire in the materials presently used, while it took 3 to 5 kg for the materials proposed for the future.

One is able to predict the tendency for carbonization of the material (therefore, its resistance to fire) on the basis of the molecular structure; the following materials are listed in order of decreasing tendency of carbonization: polyphenylene, polybenzimidazoles, phenolics, polyisocyanurates, polyurethanes, and epoxides.

The given physiochemical properties are inadequate to detemrine the real toxicity of materials and it is absolutely essential to perform experiments with animals.

One comprehensive study[69] has been devoted to this approach to the problem.

Two ways of research are analyzed. (1) The first examines the principal characteristics of the toxic effect and looks for the probability of survival: Professor Boudene and his collaborators.[70, 71] Chatenay-Malabry have focused on a model fire and on a model animal very close to reality and very much used in France; the results are displayed in the form of a physiogram. (2) The second approach of research is directed to the study of the starting time at which the gases of combustion of the material are able to induce conscious or unconscious poisoning to the point at which all flight becomes impossible.

The team of Professor Einhorn[72] exposes rats in a chamber composed of a grilled floor and a small lever manipulator. The rats have been trained to avoid electric shock by manipulating the lever.

The team of Smith, et al[73] uses a tumble cage to measure the time to incapacitance. The combustion is carried out in a turbulent flow furnace, from which the atmosphere is recycled, passing through the turning cage at a fixed speed in which the rats are exposed (150 to 300 g in weight). The materials represent 15 standard polymers. Acrylonitrides and Douglas fir are the most dangerous, the PVC rating in 10th position, polyurethane foam in the 7th. The best results have been obtained with polyphenylene sulfide.

The team has been able to express the inhalation dose of CO and HCN which causes incapacitance in rats: CO = 15.4 mg/Kg. For death, CO = 50.5 mg/Kg.

For HCN, the precision is not as good. T_{incap} = HCN: 320 μg/Kg

T_{death} = HCN: 1.95 μg/Kg.

The calculations for humans permit only to say that the total concentration is 3.4 μg of CO per ml of blood.

The team of Dressler[74] uses similarly a turning cage with imposed speed (10 t/min) for the determination of the time of incapacitance and the time to death.

The materials subjected to the test are represented by three carpets used in aircraft. One has determined the time to death, of useful function (TUF), and of loss of consciousness; it is the rug C which is the least dangerous. It is followed by rug A, then rug B; however, a correlation between the time to death and the time of useful function has not been determined.

The NASA team and University of San Francisco utilizes an exposure chamber[75] which is able to hold 4 mice: The study takes into account at the same time, the time to incapacitance and lethal concentration or time of death. Four groups of materials have been studied: Synthetic polymers, synthetics without sulfur or chlorine, synthetic polymers with chlorine, synthetic polymers with sulfur and natural polymers. In the main, death occurs between 1 and 3 minutes after the first signs of incapacitation - 8

relative classifications of materials according to their toxicity are proposed in this paper: they are formed between 2 parameters t° = 600°C and 800°C and two ventilations: 0 ml/sec and 48 ml/sec.

One can make these general remarks: Wool, Douglas fir (wood), oak, hemlock - cause signs of incapacitance sooner than other materials.

Wool causes death most rapidly; it is followed by polyethylene, nylon 6, Douglas fir, and oak (in 3 cases out of 4).

The polyether sulfones appear to be among the least toxic. The polycarbonates are intermediate.

In this same chamber, have been studied flexible foams:[79] The polyrethanes are more toxic than the polychloroprene (neoprene). Ventilation decreases toxicity.

The same team USAF/NASA[76] has studied always under the same conditions as airplane seats: 9 flexible foams and 9 seat covers; the lethal concentration and time to death have been pointed out for each material - the classification given according to the lethal concentration and the time to death which are not always identical.

Wool covers are the most toxic confirmed by reference 75, neoprene is less toxic than polyurethane, confirmed by reference 77.

Other studies of the cellular polymers have been made by the same team[78] as well as on the synthetic materials of interest to aircraft.[79] In the last article, a relative classification, beginning with pyrolysis between 200 and 800°C, taking into account the time to incapacitation and to death, showed polyurethane flexible foam to be most toxic; the untreated polycarbonates were among the least toxic, PVF and polystyrene had a good ranking.

PVC and phenylene oxide rated as less toxic if one referred to the time to death and more toxic if one referred to the time to incapacitation.

The research in the area of toxicity continues actively. For additional emphasis, one can consult "Annual Conference on Fire Research", published by NBS[80] and Birky[81] - a program with the objective of finding a method permitting the evaluation of the toxicity of products of combustion: two fire models are proposed: a quartz-iodide lamp and furnace with two modes of measurement of incapacitation. One is the method of Smith - turning cage with imposed speed, the other the method of Packam involving hind leg flexure technique.

At the University of Utah (Einhorn) there existed a contract[82] which proposed work in three directions. (1) Develop a procedure for obtaining a relative measure of the toxicity of burning materials and evaluating fire modes, the models of exposing animals, etc. (2) Study theoretical density of smoke. (3) Study the thermal degradation of polymers.

3.3.2 Full-Scale and Sub-Scale Studies

The opinions are divided on the utilization of sub-scale and full-scale studies, some affirming that these are very costly for the information that one receives. However, there are those who are able to tell us that conclusions given by laboratory studies are correct and realistic.

The extensive studies of E.N.I.C.A.[69] have made the point that full-scale studies in Europe and the USA should continue (we have also heard of studies in Great Britain). Some of the past studies are: ALPA in 1966[83] and 1968,[84] NASA in 1974[85] and 1976,[86] and FAA in 1965 and 1970.[87]

All of these tests have consisted of studies of the behavior of fire of the materials used now or likely to be used in aircraft cabins. One is able, however, to assess the danger presented by materials before 1966 (before the present regulations): these present a bad tendency to flashover while the modern materials limit this tendency. The future materials proposed by NASA are very conclusive but also very expensive.

CEAT (Center for Aeronautical Testing of Toulouse) has an installation for semi-scale testing in which one can study the parts of cabins (panels, seats, curtains, etc.).[88,89] The materials are placed in the center of the cabin (8 m^3) at the initiation of an alcohol fire with two conditions of ventilation. 0 m^3/hr and 148 m^3/hr; in the configuration the material does not propagate flame under the conditions of the test; ventilation plays a beneficial role by the dilution of the smoke and the toxic gases. Seat foams of polyether polyurethanes are vulnerable and emit very much smoke, the same as laminated epoxides.

GE[90] has initiated a study in true scale with panels of polycarbonate lexan; the authors have tried to find a correlation with laboratory tests (ASTM E162) without success. The combustion of the thermoplastics varies with humidity: it is favored by an increase in relative humidity, contrary to wood which burns poorly in humid conditions.

3.3.3 Full-Scale and Sub-Scale Tests with Animal Experiments

One is aware principally of the work done by NASA/USF/workers in this area.

The tests of toilets and baggage compartments[91] have been made with the cooperation of Boeing and Douglas. These elements of the aircraft are vulnerable principally in the large carriers. The animal experiments use the system of "Gaume" AETS: 6 mice in a turning cage and a rat equipped with transducers for breathing and pulse.

There was no propagation of flame in the B747 model toilet during the 30 minutes of testing. The animals die principally from the combined hypoxic effects of HCl and HF and from the elevated temperature; CO has very little contribution in the hypoxia: lower concentrations of toxic gases were recorded in the test animal enclosure.

NASA has conceived an experimental chamber of 84 liters copied after the small chamber of 4.2 liters used in the laboratory studies.[92,93] This chamber can hold 36 mice, 8 rats, 4 rabbits, or a combination of two species. It is divided into independent compartments which can be withdrawn at any time without disturbing the test. The animals are observed directly through transparent walls. One takes as the time of incapacitance the loss of equilibrium of the animal, prostration, or appearance of convulsions. As time to death, one takes as an indication the cessation of movement and respiration.

The dead animals undergo a blood sampling as well as one-half of the live animals, the other half are destined for brain sampling.

The sub-scale tests at CEAT with animal experiments have made use of two species of animals: rats and rabbits. The exposure chamber[94] measures 2.5 m^3 and contains 8 tumble cages (8 rats) and a screened cage for the rabbits.

The rats are submitted for clinical observation to measure the time of incapacitation (loss of consciousness which is evidenced by the non-reaction of the animal to an electric shock); half of the rats are sacrificed for blood tests (C, O, H, B, etc.), and brain material in order to judge the ability to recuperate.

The rabbit, in spontaneous breathing, is equipped with electrodes and telemetering transducers which transmit heart, breathing, and brain frequencies.

The first studies were made in March and May, 1978, which enabled to be found a correlation between the known physico-chemical combustion gas properties, and the incapacitation and toxification of the laboratory animals.

The annual report of NBS[80] states that contracts have been made with universities to study the toxicity of the products of combustion.

Thus, Johns Hopkins University (Annan and Call[95]) propose to work with rats trained to manipulate a lever to avoid a shock.

Einhorn and his collaborators[82] propose to develop a procedure which permits the evaluation of the toxicity in a simple and reproducible manner by a method which can be used in all laboratories.

3.3.4 Conclusion

In only three years, one does not know very clearly the problem of the toxicity of the materials of construction in an aircraft cabin. Since much work has been conducted and all of the researchers agree that work with animal experiments is indispensable: they have the merit of being able to give a relative classification of the materials according to their toxicity, which permits one to find a method of regulation.

3.4 Aircraft Structural Materials

Principal aircraft structural materials are aluminum alloys, stainless steels, titanium alloys, magnesium, and composites.

Unfortunately, the combustion of metals and particularly composites have not been investigated as thoroughly as that of liquids and plastics, and, consequently, the availability of data is much more meager. The latter situation is not too surprising since structural metals and alloys do not pose a fire threat under normal environmental conditions. As the application of metals has been pushed into more severe operating environment regimes, particularly higher temperatures, research has also been conducted toward an understanding of the oxidative-corrosion problem that results. These studies are considered pertinent to the combustion problem since they may provide some understanding of the reaction mechanisms involved up to the point of metal ignition. Once catastrophic oxidation (flame) has been initiated, other mechanisms obviously may control the sustenance of the flame process. The subsequent discussion will endeavor to review the physico-chemical properties of selected "neat" metals as relates to their slow oxidation behavior (pre-ignition) and their catastrophic combustion behavior (flame burning).

3.4.1 Compilation of Physical and Thermodynamic Data for Selected Materials

The bulk of data included in the following table has been extracted from the excellent compilations available in references 96 and 97.

Table 3.10 provides data on the melting and boiling point temperatures as well as the heats of formation of selected metals and their oxides. Also included in Table 3.10 is the volume ratio (R) or sometimes referred to as the Pilling-Bedworth Ratio and pertains to the ratio of the metal oxide volume to the atomic volume of the metal where both volumes refer to equivalent amounts of metal. R is determined as follows:

$$R = \frac{\bar{W}d}{n\bar{D}w}$$

where n = number of metal ions in a molecular formula of oxide (Al_2O_3, n=2; CuO, =1)

$\bar{W}$ = molecular weight of oxide

w = molecular weight of metal

$\bar{D}$ = density of oxide

d = density of metal

The volume ratio provided an early basis[98] for ranking the oxidation resistance of metals. According to Pilling and Bedworth, an:

$R < 1$, insufficient oxide was present for protection
$R \approx 1$, was considered ideal
$R \gg 1$, provided a surface susceptible to pealing and cracking and, therefore, did not provide adequate protection.

The volume ratio provided a fair qualitative basis for ranking the oxidation resistance of metals. It is now known that there are other properties equally important in determining oxidation resistance. According to Fontana and Greene,[98] to be protective, an oxide must possess: (1) A coefficient of expansion nearly equal to that of the metal substrate. (2) Good adherence. (3) A high melting point. (4) A low vapor pressure. (5) A good high temperature plasticity to resist fracture. (6) Low electrical conductivity or low diffusion coefficients for metal ions or oxygen. (7) A volume ratio close to 1 to avoid compressive stresses or lack of complete surface coverage. Many metal-oxygen phase diagrams indicate several stable binary oxides. For example, as shown in Table 3.10, iron may form the compounds FeO, Fe_2O_3. In the oxide-scale formation on base metals, generally all of the potentially stable oxide phases are formed in sequence. The most oxygen-rich at the scale-gas interface and the most metal-rich compound at the metal-scale interface, i.e., Fe, FeO, Fe_3O_4, Fe_2O_3, O_2.

3.4.2 Oxidation Characteristics

In order to assess the effects of environmental conditions on the ignition and flame propagation characteristics of metals, it is necessary to understand the mechanisms of the chemical oxidation reaction. It is well-known that the oxidative reaction proceeds by a series of steps, the slowest one controlling the overall rate of reaction. By comparison of the relative rates of occurrence of these steps, it appears that only three are slow enough to be rate controlling. These are (1) the rate of transport of oxygen to the reacting surface, (2) the rate of adsorption of oxygen molecules at the surface, and (3) the rate of diffusion of ions in the oxide.

The rate of oxidation of a metal is commonly measured and expressed as weight gain per unit as a function of time. Various empirical rate laws have been observed.

Linear $$W = K_{\ell} t$$

where W = weight of oxygen per unit surface area that has reacted in time, t.
K_{ℓ} = rate constant

The linear rate is characteristic of metals for which a porous or cracked scale is formed. In other words, no diffusion barrier exists between the two reactants.

Parabolic $$W^2 = K_p t + C$$

Pure metals exhibiting an ideal ionic diffusion controlled oxidation mechanism should follow this rate. Results in a thick coherent oxide coating which is fairly common with iron, cobalt, and copper.

Logarithmic $$W = K_{\ell g} \log (Ct + A)$$

This rate behavior is generally observed with thin oxide layers (<1000A°) at low temperatures with metals such as aluminum.

TABLE 3.10

Properties of Selected Metals and Their Oxides

Metal	Oxide	Melt Point °C	Boil Point °C	Oxide Melt Point °C	Oxide Boiling Point °C	Volume Ratio, R	$-\Delta H^o_{298}$ KCal/M
Al	Al_2O_3	659	2450	2030	dec	1.28	400.0 ± 1.5
Be	BeO	1288	2400*	2520	3850	1.59	143.1 ± 3.0
B	B_2O_3	2050	-	450	2300*	-	306.1 ± 4.5
Cu	CuO	1083	2570	dec	-	1.68	37.1 ± 0.8
Fe	FeO	1535	3070	1378	dec	0.63	63.2 ± 0.3
	Fe_3O_4	1535	3070	1594	dec	2.10	266.9 ± 1.0
	Fe_2O_3	1535	3070	1457**	-	2.14	196.3 ± 0.8
Mg	MgO	650	1105	2852	3600	0.81	143.7 ± 0.2
Ti	TiO_2	1667	3285			1.95	225.5 ± 1.0
WC	-	2870 ± 50	6000	-	-	-	9.1 ± 2.5

*Extrapolated
**Peritectic Decomposition

TABLE 3.11

Oxidation Data for Selected Metals

Metal	Primary Oxide	Gas	Press Pascal	Temp ^{o}C Range	Ap $(g^2/cm^4\text{-sec})$	Al $(g/cm^2\text{-sec})$	Ep or El (CAL/MOLE)
Al	Al_2O_3	O_2	1.0×10^5	176 - 246	$2\text{-}7.5 \times 10^{-8}$	-	22,800
Be	BeO	O_2	1.3×10^4	449 - 521	0.22	-	62,000
	BeO	O_2	1.0×10^4	176 - 371	1.8×10^{-12}	-	8,500
	BeO	O_2	1.0×10^4	399 - 510	3.5×10^{-3}	-	50,300
Cu	Cu_2O	Air	1.0×10^5	149 - 288	1.5×10^{-5}	-	20,140
	CuO	Air	1.0×10^5	288 - 482	0.266	-	37,700
Fe	FeO	Air	1.0×10^5	260 - 593	0.37	-	33,000
Mg	MgO	O_2	1.0×10^5	247 - 302	-	1.7×10^6	50,500
Ti	Rutile	O_2	1.0×10^4	204 - 316	2×10^{-5}	-	29,300
	Rutile	O_2	1.0×10^5	343 - 443	-	400	40,000
	Rutile	O_2	1.0×10^5	443 - 510	-	5	47.000

<u>Cubic</u> $$W^3 = K_C + C$$

Not commonly observed. In general, the oxidation behavior of technically important metals can be classified as either linear or parabolic. Actually, equations (1) and (2) are temperature dependent as shown by the substitution of the true meaning of K and K_p, below:

$$W = K_\ell t + A_\ell e^{-E_\ell/RT_t}$$

$$W^2 = K_p t + C = A_p e^{-E_p/RT_t} = C$$

In these equations, E is referred to as the activation energy, and A as the action or frequency constant. The constants A and E, in general, depend on environmental conditions and may even be functions of the metal temperature. Experimental values of A and E for several metals are given in Table 3.11. Both A and E, because of experimental determination limitations, have high uncertainties.

Reynolds[99] has investigated the ignition temperatures of solid metals. Since ignition is brought about by the exothermal oxidation reaction between the solid metal and its gaseous environment, one would expect the process to be related to the relatively slow oxidation that occurs on metals at low temperatures. Sustenance of the combustion process, viz. burning after ignition occurs may, however, proceed by any of several mechanisms such as a surface reaction or a vapor phase reaction. The remainder of this portion of the discussion will be directed to a review of the ignition of metals and the influence of environmental factors. In a subsequent section of the report, the burning behavior of metals will be further explored.

Reynold's investigations involve analytical and experimental efforts on the ignition of a number of structural alloys for aircraft use. Reynold's developed a simple definition of ignition from an energy balance on an isothermal body. He defined ignition temperature as being equivalent to the temperature at which the body temperature began to increase at an increasing rate. Experimentation involved dynamic flow and the results are given in Table 3.12. Air and oxygen at pressures of 1 to 7 atmospheres were evaluated. In this investigation, the oxygen content and pressure had no effect on ignition temperatures. Temperatures are given for static air first, then for an air flow of Mach 1.25. The term "brightness temperature" refers to the temperature at which exothermic reaction appears to start.

If the protective oxide is removed from or not present on a metal, and the metal is quickly subjected to an oxidizing atmosphere, ignition can take place at low temperature. The process is referred to as a pyrophoric reaction. The process is typically experienced with powdered metals or metal fragments possessing very high surface to volume ratios. This type of reaction is deeply involved in the generation of sparks from grinding wheels, or from a cigarette lighter "flint".

A number of investigations of the ignition of metals have been conducted. In general, the factors affecting the ignition temperature of a metal are quite diverse and include: the purity of the metal; properties of the oxide coatings such as its melting point, adherence, porosity, and ability to withstand mechanical stress, cracking, or thermal stress cracking; gas composition including moisture content; pressure velocity or air flow at the surface; state of subdivision of the metal; previous history of the metal and the experimental apparatus and technique employed. Previous investigations also show that metallic alloys can have ignition temperatures unlike either metal constituent alone.

In terms of the affect of the pressure regime experienced by aircraft (sea level to 21,336 meters - 70,000 feet - altitude), one would expect the change in partial pressure of O_2 to influence the ignition temperatures of metals. In general, previous studies indicate little affect of pressure on ignition temperature (see, for example data in Table 3.12). Consequently, any difference in air pressure from sea level to flight altitudes, as it affects ignition, appears to be negligible.

3.4.3 Combustion of Metals (General)

In the previous section, we have discussed the oxidation of metals up to the point of ignition, that is the point where the rate of heat generation exceeds the rate of heat loss and self-sustaining combustion process, sometimes referred to in the literature as catastrophic oxidation, takes place. The combustion of solid metal fuel particles and foils has been investigated for some time because their high light yields make them useful as light sources for photography and their high heat content makes them potentially useful ingredients of rocket propellants.

If we compare the free energies of the oxidation reaction between metals and oxygen, it is very evident that, from a thermodynamic viewpoint, the preferred state is that of the metal oxide. In addition, the heat of formation of many oxides from solid materials such as Al, Be, B, Mg, etc., is very large, implying that combustion should be vigorous and result in very high flame temperatures. Obviously, the propensity of a particular reaction to proceed to predicted thermodynamic end points is governed by a

TABLE 3.12

Ignition Temperatures of Solid Metals

Metal	Ignition Temperature °C	Gas	Pressure atm
Mild Steel	1227 to 1277[a]	Air[b]	1 to 7
W	1243 to 1287[a]	Air[b]	1 to 7
Ti Alloys:			
RC - 70	1582 to 1623[a]	Air, O_2	1 to 7
RS - 70	1587 to 1616[a]	Air, O_2	1 to 7
RS - 110A	1571 to 1599[a]	(C), O_2	1 to 7
Stainless Steels:			
430	1349 to 1367[a]	(C), O_2	1 to 7
302	d	Air, O_2	1 to 7
Mg[e]	633	O_2	1 to 10
Fe[e]	930	O_2	1
Al[e]	d	O_2	1

[a]Brightness temperature

[b]Not testing in oxygen, but probably ignites in oxygen at about the same temperature

[c]Does not ignite in air

[d]Melts before igniting

[e]References by Reynolds - Other Source

number of additional factors such as the physical state of the metal, physical dimensions, and factors influencing the kinetics of reaction; for example, the fuel and oxygen transport processes that are involved in maintaining the reaction. One, therefore, must distinguish between metal particle combustion and bulk metal combustion processes. One must also distinguish between the parent metal and its oxide properties such as melting point, boiling point, adherency, porosity, etc., as influences the particular mode of combustion to be followed and the tendency for flame sustenance versus self-extinguishment. For example, bulk aluminum conducts heat away at a rate such that the burning surface is usually cooled below the ignition temperature and flame cannot be sustained. However, small aluminum particles burn rapidly. The heat of vaporization of most metal oxides is so large that the boiling point puts a practical limit on flame temperature.

3.4.3.1 Metal Particles and Dust

Metals ignite most readily when in dust layers.[100] The greater division of the metal results in both a higher surface to volume ratio and, consequently, a higher rate of heat production per unit volume, and a lower cooling rate. If the surface to volume ratio is very large, the conduction of heat from the combustion zone by the metal is greatly reduced. Heat loss is then by the relatively slow process of radiation, convection, and conduction in a gas, and this leads to neighboring particles of metal reaching the ignition temperature with great rapidity. If the finely divided powder is loosely packed together, the heat loss by convection is largely eliminated and excellent opportunity for spontaneous ignition of the metal exists. Many fires of the latter type have occurred industrially, for example, in the storage of zirconium metal shavings in dumps.

Metal dusts suspended in air and flowing through a furnace of predetermined temperature have a well-defined ignition temperature. The actual ignition temperature of a metal dust depends on a number of other factors such as dust concentration, oxygen concentration, particle size, extent of surface oxide layer, etc. Values in Table 3.13[101] are minimum values. Similar dependence for ignition exists for condensed electrical sparks. Some metals, for example, magnesium and titanium, are easily ignited in CO_2. It should be noted that in the absence of any oxide layer, many powdered materials, as previously mentioned, ignite in air at room temperature. Metal dust-air mixtures like vaporizable fuels exhibit limits of flammability. These are expressed as a minimum concentration in gr/liter-air. Typical values are: Al - 0.035, Mg - 0.020 and Ti - 0.045. In general, metal powders have very wide limits. This is indicated by safe O_2-N_2 mixtures which no longer support combustion. For Al, this is 9 volume percent O_2, but for Mg it is only 2%. In the latter case, N_2 no longer seems inert.

Flame propagation in metal dust clouds appears to be a discontinuous layer to layer process similar to flame propagation through hydrocarbon mists. Burning velocity of dusts range from 20 to 100 cm/sec for aluminum depending on particle size. Explosion pressures associated with metal dust-air mixtures as a result of combustion in confined volumes are just as great, if not greater, than those of gaseous fuel-air mixtures; however, the rate of pressure rise is lower.

3.4.3.2 Bulk Metals

As implied earlier, the ignition and combustion of metals is strongly influenced by the physical size of the specimen. Consequently, one would expect the behavior of metals in bulk form to be very different. If bulk metal is heated in a furnace in the presence of O_2, only slow oxidation occurs below the ignition temperature. Above the ignition temperature, Al and Mg, for example, form pools of burning molten metal that float on top of the molten oxide. These burning pools emit light of great brilliance. Oxygen seems to be essential for the combustion of aluminum in bulk as combustion dies out when air is admitted.

3.4.3.3 Combustion Models

Brzustowski, Mellor and Glassman[102,103] have conducted considerable analytical and experimental investigations on the combustion of metal particles, particularly by Al and Mg in air, O_2 - Argon and Argon - CO_2 atmospheres at various pressures. The high heats of vaporization generally limit the temperature of metal-oxygen flames to the boiling points of the respective oxides. Aluminum and magnesium can burn in the vapor phase because their boiling points are lower than those of their oxides. Although the above criterion is a necessity for vapor phase diffusion burning, it is not sufficient in view of the pre-ignition oxidation reactions that can take place which can inhibit vapor-phase combustion. In the case of single magnesium and aluminum droplet combustion, Glassman, et al, have developed a combustion model which is an extension of the quasi-steady state vapor phase diffusion flame previously used to describe the combustion of hydrocarbon droplets. The theory was modified to consider flame radiation, transport of condensed oxide products, and evaporation of the metal. Good results were obtained for the burning rate and flame radius. The region of validity of the diffusion flame model was also investigated experimentally by Glassman, et al.[101-103] Aluminum wires and magnesium ribbons were formed in mixtures of oxygen and argon at pressures

TABLE 3.13

Some Ignition Characteristics of Metals

Element	Melt Point, °C	SIT Dust, Air, °C	Ignition Bulk, O_2, °C	MIE Dust, Millijoules	Remarks
Al	660	645	>1,000	20	--
B	2300	730	--	--	No ignition by Spark
Be	1280	--	--	--	--
Mg	650	520	625	20	Can be ignited by spark in CO_2
Ti	1730	330	--	25	Ignites in N_2 and CO_2 under favorable conditions

SIT = Spontaneous Ignition Temperature

MIE = Minimum Ignition Energy - Electrical

TABLE 3.14

Selected Properties and Burning Mechanism of Metal Particles

Metal	Metal MP°K	Metal BP°K	Oxide	Oxide MP°K	Oxide BP°K	VOxide/VMetal	Burning Mode
Porous Oxide							
Li	454	1620	Li_2O	1700	3200	0.58	Vapor phase diffusion flame
Mg	923	1381	MgO	3075	3350	0.81	Vapor phase diffusion flame
Insoluble Oxide							
Al	932	2470	Al_2O_3	2318	3800	1.45	Vapor phase diffusion
Be	1556	2750	BeO	2823	4123	1.68	Vapor phase diffusion
Si	1685	3582	SiO_2	1883	3000	--	Surface
Soluble Oxide							
Ti	1950	3550	TiO_2	2128	4100	1.73	Surface
Zr	2125	4650	ZrO_2	2960	5200	1.45	Surface
Volatile Oxide							
B	2300	3950	B_2O_3	723	2520	--	Surface

from approximately 6.9-3100 kp/meter^2 (1 to 4500 psia). Magnesium ignited in a vapor phase reaction above the ribbon. The initial flame spread at a speed of several centimeters per second. Aluminum ignited when the accumulated oxide coating melted and exposed liquid metal to the oxidizing atmosphere. The metal samples were ignited by resistance heating in a test chamber at ambient temperature conditions. The vapor phase diffusion flame model was shown applicable to magnesium ribbons over most of the range investigated and to aluminum wires at the lower pressures. Investigations were then extended to carbon dioxide, oxygen, and carbon dioxide-argon mixtures. In carbon dioxide-oxygen mixtures, anodized aluminum wires exhibited the same combustion characteristics as in Ar-O_2; the power required for ignition decreased and was a minimum for pure CO_2. The combustion of Mg was altered more appreciably by presence of CO_2. In particular, the region of no ignition was greater for CO_2-O_2 than O_2-Ar. Magnesium would not burn in CO_2-Ar mixtures.

Table 3.14 summarizes some of the pertinent properties or selected metal particles and their apparent mode of combustion.

Magnesium has a vapor pressure of about 1 mm Hg or more at 1000°K. Its boiling point is much lower than the boiling point of its oxide. In addition, MgO forms a porous surface coating and is not able to seal the metal against surface oxidation. Consequently, one would expect Mg to exhibit a vapor phase diffusion flame process as has been observed experimentally.

The oxides of Al, Be, and Si are protective materials which adhere well to the metal surface and would be expected to inhibit oxidation over a wide temperature range.

Both Ti and Zr show the ability to form a solid solution of oxide in the metal. There is no distinct interface between the oxide and the metal. Oxygen can diffuse through the oxide at a low but finite rate. As a result, combustion can take place even if the metal is covered with a layer of solid oxide.

The oxide of boron melts at a low temperature and has a relatively low boiling point. It is, therefore, expected that diffusion of metal and oxygen through the liquid oxide and at higher temperature, the evaporation of oxide and diffusion of oxide vapors away from the surface may be significant in the combustion process.

Inspection of Table 3.14 indicates that Al, Be, Ti, and Zr boil at temperatures exceeding the boiling points of the respective metals. The oxides of Si and B boil at temperatures lower than the metal boiling point. Accordingly, using Glassman's criteria for vapor phase burning, this indicates that Al, Be, Ti, and Zr can burn in diffusion flames and Si and B cannot. However, due to heat transfer consideration, Ti and Zr may never develop a diffusion flame.

No specific studies of the combustion of bulk metals was uncovered. In general, the combustion of bulk metal would be expected to be much more difficult because of the small surface to volume ratio present. In addition, the high thermal conductivity of metals as well as the high mass of metal present provides an excellent heat sink for any energy releases occurring on the metal surface. As a result, the achievement of local ignition and sustenance of combustion once ignition has occurred will be much more difficult compared to metal fragments. As a metal is exposed to a high temperature environment and becomes heated, the prospects for sustained combustion improve. The latter situation, of course, exists in aircraft crash environments where the large, long duration heat release from burning jet fuel provides for elevation of metal temperature in bulk so that ignition and combustion of metal elements is possible. In order for metals to become involved in the crash fire, their ignition temperatures must be below or equal to the flame temperature generated by the jet fuel diffusion flame, viz ≈ 2000°F (≈1100°C).

3.4.3.4 Flame Temperature of Metals

Dusts suspended in air or oxygen burn vigorously and a stationary burning flame can be achieved by loading air continuously with dust. Wolfhard and Parker[104] studied such a premixed aluminum flake/air flame of about 20 cm cross section. They report that the heat radiation from the flame was such that it was impossible to stand nearby; the spectrum of the flame was continuous with weak $A_{\ell}O$ bands. The color temperature of the continium was about 3900°K (6560°F). This coincides roughly with the boiling point of Al_2O_3 (3800°K). As indicated previously, the boiling point of the oxide is an upper limit for the adiabatic flame temperature since the heat of vaporization of Al_2O_3 is so large that only partial vaporization can occur with the available heat of combustion. As pointed out by Wolfhard, the color temperature which is a radiation measurement provides an average flame temperature and not the true flame temperature.

Magnesium-air flames also emit continuous radiation with a color temperature of 3900°K. The boiling point of MgO is ≈ 3350°K (≈5570°F). In the case of Ti and Zr, Harrison[105] reports that qualitatively the flame temperature of these metals was similar to that of Mg. In general, it is quite apparent that combustion of metals

produces very high local temperatures which make burning metal particles a potent ignition source and extinguishment of bulk metal fires a difficult task. In the latter case, the difficulty is aggravated because of the reactivity of the burning metal with common extinguishants such as water, CO_2 and halogenated hydrocarbons.

3.5 Fire Intensity

Under the general heading of "fire intensity" one would normally consider most flammability properties or characteristics of materials with the possible exception of those parameters associated with ignition behavior. In a few instances, even this arbitrary division between ignition properties and fire intensity characteristics breaks down and is not clear whether a test method is evaluating ignition or flame spread phenomena (often a series of multiple ignition points).

3.5.1 Test Methods

If one considers the test methods and standards available for the evaluation of the flammability characteristics of gases, liquids and solids (Hilado[106]), the situation is as follows: For gases, provided that vessel dimensions are of reasonable size, the measurement of a wide variety of properties by many investigators in many laboratories results in good agreement of the data. As a consequence, there has not been a need to further refine and standardize the methods of testing gases.

For liquids, a greater degree of specification of the testing procedure is required in order that comparable data can be obtained by many investigators. Measurements of the flash point and fire point of liquids are examples of this situation. Hilado[106] discusses the standardized flammability tests for liquids. Many other flammability tests for liquids such as the rate of flame spread over the surface of a pool of liquid (at temperatures below the flash point of the liquid) have been reported in the literature (Glassman and Hansel,[107] Roberts,[108] etc.) but have not been standardized and the data from such tests do not represent commonly tabulated information. Precisely because such procedures have not been standardized, conflicting data can be found in the literature and controversies arise.

For solid materials, the tests for flammability characteristics are at the opposite extreme from the situation that existed for gases. In almost all cases, the parameter being measured is not a fundamental property of the material undergoing test and is subject to an extremely large number of influences in addition to the material composition, etc. Because of a lack of knowledge of what type of test to perform to obtain a fundamental property or characteristic of the material, a wide variety of tests have arisen in which the details of the test procedure are rigidly established (and as a consequence, different investigators can obtain data in good agreement with one another), and the material undergoing test can be ranked on a relative basis. In many tests, some type of numerical scale is developed to quantify the relative level of performance.

The dilemma faced by the person who must actually design equipment or components while considering flammability aspects is that the flammability data are not absolute but relative, and further, the basis of the tests on which these relative measurements were made, may or may not be appropriate to the design situation.

This topic was addressed in the recent report of the National Academy of Sciences.[109] In summary their recommendations are for the following course of action: (1) Undertake basic property tests where appropriate. (2) Pattern the laboratory scale tests as closely as possible on the real fire situation (as indicated by an analysis of past fire accidents and incidents). (3) Undertake large-scale mockup tests (e.g., lavatory modules). (4) Conduct well-planned full-scale fire tests.

The Flammability Test Methods Handbook[106] presents a good compilation of those tests which are sufficiently well developed to have been accepted as a standard by such agencies as the ASTM, NBS, etc. In addition to discussion of the tests and the full texts of some tests, a useful bibliography has been presented. However, as indicated earlier, there are many other tests of flammability characteristics which appear in the literature but which have not been standardized.

Kuchta[110] discusses in general terms a number of parameters which indicate the likely extent of fire and explosion damage (in effect the degree of fire intensity). Included among the parameters discussed are flame temperatures, heats of combustion, explosion pressures, heat fluxes within fires, etc. These parameters and others are discussed in the following sections.

3.5.2 Flame Temperatures

The magnitudes of flame temperatures can be one indication of fire intensity. Adiabatic flame temperatures for stoichiometric combustion in air for many materials are readily available in tabulated form in handbooks, manuals, combustion texts, etc. Kuchta[110] indicates that for saturated hydrocarbon vapor-air mixtures (stoichiometric),

adiabatic flame temperatures are about 1927°C (3500°F) for constant pressure combustion, and in excess of 2760°C (5000°F) for combustion in oxygen. In the case of unsaturated hydrocarbons or for combustion at constant volume, the temperatures are somewhat higher.

In the case of organic combustible solids, the flame temperatures are of the same order as those for hydrocarbons (Kuchta[110]).

It should be apparent that in most real fire situations, the actual flame temperature (as opposed to the stoichiometric, adiabatic flame temperature) will be dependent upon many factors which determine the rate of air supply, the degree of mixing of fuel and air (or oxygen), and the nature of the heat losses as determined by convective, conductive, and radiative heat transfer modes, but as an approximation the flame temperature will fall between the adiabatic flame temperature and about half that value.

In the literature, there exists a number of studies in which flame temperature in simulated fires of aircraft fuels were measured (Sarkos,[111] Geyer,[112] Graves,[113] Neill, et al[114] Russell and Canfield,[115] and Gordon and McMillan[116]) Figure 3.7.23 from Kuchta[110] and attributed to Sarkos, presents temperature-time data for the aircraft skin, cabin wall, and cabin air for a fully developed aircraft fuel fire. Kuchta indicates that the cabin wall and air temperatures will be a function of "the skin material, insulation and sealant materials, and the size of cabin vents or unsealed areas". The need to develop fire scenarios to guide the direction of future full-scale tests is obvious when one considers the multitude of factors affecting flame temperature, heat fluxes, evolution of toxic gases, etc.

3.5.3 Heat of Combustion

Another material property which has an influence on fire intensity, is the quantity of energy on a per unit mass basis which is released when a material is burned, namely, the heat of combustion. This property too can be readily obtained from tabulations in handbooks. In the case of new composite materials, such data may be somewhat more difficult to locate, although the calorimetric measurement of this property is in principle a simple measurement.

As pointed out in the report of the National Academy of Sciences, when materials are selected or screened for application in aircraft interiors, the heat of combustion is a property which is usually not given any consideration. The authors speculate that the rationale for such action is that if the material can be kept from igniting, its heat of combustion is an unimportant quantity. However, Kuchta notes that with the high flame temperatures experienced, it is unlikely that most materials could "withstand a fully developed aircraft fire without being consumed or severely damaged".

In the case of solids which decompose or pyrolize when heated, the temperatures and rates at which flammable gases are evolved, and the nature of the pyrolysis process (endothermic, exothermic) are perhaps more important than the heat of combustion. Although such data are also related to the ignition characteristics of these materials, they are equally measures of the fire intensity of solids.

3.5.4 Explosion Pressures

When flammable vapor-air mixtures undergo combustion, the considerable release of energy can result in a significant rise in pressure if the heat release occurs within some type of containment. The magnitude of the pressure rise will be a function of the many variables which influence the rate of heat release (stoichiometry, mixing, etc.) and the degree to which the container is vented.

Kuchta indicates by example that a constant volume methane-air mixture at one atmosphere would experience a pressure rise to 6.2×10^5 Pascal (90 psia) or 896×10^5 Pascal (130 psia) for lower limit and stoichiometric mixtures, respectively. Such values are the result of application of the perfect gas law equation of state ($PV = nRT$) for the initial and final states of the gas mixture, and the assumption of constant volume. Therefore

$$P_f = P_i \left(\frac{n_f}{n_i}\right) \left(\frac{T_f}{T_i}\right)$$

For explosions (deflagrations in spherical combustion chambers in the absence of large heat losses), Kuchta presents the following expression for the pressure rise:

$$\Delta P = K\ P,\ S_u^3 \frac{t^3}{V}$$

Where ΔP = pressure rise
K = empirical constant
S_u = burning velocity
t = burning time
v = chamber volume

For the time required to reach the maximum overpressure, Kuchta presents an expression from Zabetakis[117] applicable to paraffinic hydrocarbon or fuel blends.

$$t = 75(V)^{1/3} = 2.124(V^1)^{1/3}$$

Where t is measured in milliseconds
V is measured in ft^3
V^1 is measured in m^3

3.5.5 Heat Fluxes Within Fires and Radiation Flux to the Surroundings

Of considerable importance to both the rate of fire spread and to the possible survivability of humans, is the level of thermal radiation from flames.

Generally the radiation from these flames whether supported by gaseous, liquid, or solid fuel sources, is complicated because of the production of carbon in the flame which radiates as well as the usual hydrocarbon combustion products, CO_2 and H_2O. Since the amount of air supply, the degree of mixing of fuel and air, etc., play a large role in determining both the flame temperature and the flame emissivity (as influenced by the amount of carbon formed, etc.), one usually has difficulty calculating the flame radiation by the usual methods. A useful approach has been reported by Burgess and Zabetakis[118] in which the flame radiation is reported in terms of an F factor defined as the fraction (or percentage) of the total heat release which is radiated to the surroundings. Such F factors have been measured and tabulated for a number of gaseous and liquid-supported flames.

Kuchta discusses a number of investigations in which heat fluxes within fires or in the vicinity of fires were measured. In the test of Sarkos for the full-scale JP-4 aircraft fire, measured heat fluxes were between 21×10^4 and 42×10^4 j/m^2 sec. Figure 3.7.24 presents data of Geyer for heat flux measurements for a "full-scale test where a simulated JP-4 engine fire was extinguished after a preburn time of approximately 17 seconds" (Kuchta[110]). Other data from Burgess and Zabetakis for gasoline and other hydrocarbon fuels indicate values of 84×10^4 j/m^2 sec for the maximum radiative output for large pool fires.

Work carried out in the UK by Rolls-Royce (Cahill[119] and Beardsley[120]) produced data for flame intensity (as measured by a flame intensity calorimeter inserted into the flames) for a variety of flames including a 6 inch burner propane flame, 3/4 inch butane torches used in small-scale fire testing, pool fires from various fluids used in aircraft operation, and more intense flames created by mixing additional air into the pool fires. These data indicate that in the case of the air-augmented pool fires, maximum flux levels up to 1.42×10^6 j/m^2 sec ($\simeq$125 BTU/ft^2 sec) were measured. In the case of tests carried out with atomized fuels, measured maximum heat transfer rates were of the order of 42×10^4 j/m^2 sec.

3.5.6 Radiation from Flames of Liquids in Impact Tests Versus Steady-State Tests

In the case of liquids (in particular aviation fuels) when discussing the fire intensity, it is important to distinguish between the transient or non-steady situation as recorded in the first twenty or thirty seconds following impact type situations and the quasi-steady situations in most laboratory measurements.

In the steady-state situation, it is expected that very little difference exists for the fire intensity of aviation fuels as measured by such factors as maximum flame temperature, heat release rate (or equivalently, pool surface regression rate), and radiation measured to the surroundings. The radiation measurements of Fu[121] show a slight decrease in the radiation measured from equivalent size fires of Avgas, JP-4, and JP-5, respectively, an ordering consistent with fuel volatility. Typically, for hydrocarbon pool fires, the percentage heat release measured as radiation to the surroundings will be approximately 30% (Burgess and Zabetakis[118]). On this basis, it is expected that differences in the steady-state fire intensity measurements for the various aviation fuels will be small.

In the case of the transient period following impact-type tests, there appear to be significant differences in fire intensity depending on the fuel volatility. The tabular data in Tables 3.15 and 3.16 were obtained from Russeel.[131] Measurements of fireball size and radiation intensity both indicated greater fire intensity for JP-4 than JP-8.

3.5.7 Anti-Misting Fuels

Because of the seriousness of the fuel dispersion on flammability characteristics, significant attention is currently being devoted to development of anti-misting fuels and associated tests to assess the degree of protection afforded by the anti-misting additives (Wilford,[122-124] Weatherford and Wright,[125] Weatherford,[126] Eklund,[127] Mannheimer,[128] Miller and Wilford,[129] Ahlers,[130] Russeel,[131] Wright, et al[132] Miller[133])

TABLE 3.15

Radiation from Fires in Vertical Fuel Drops with .019 m^3 of Fuel (Metal Containers) at an Impact Velocity of 60 mph (96.5 kmph)

Fuel	Watt-sec/ft^{2}[a]	j/m^2	Btu/ft^{2}[a]	j	Btu[b]	100 x Radiative Output / Available Heat[c]
JP-4	5,720	6.15×10^4	5.42	2.6×10^8	245.5×10^3	42
	3,980	4.28×10^4	3.77	1.8×10^8	170.5×10^3	29
	3,880	4.18×10^4	3.68	1.75×10^8	166.0×10^3	28.5
	3,620	3.89×10^4	3.43	1.63×10^8	155.0×10^3	26.5
	1,860	2.0×10^4	1.76	$.84\times10^8$	79.7×10^3	14

[a]Total radiation per unit area at 60feet away (18.3 m) for entire burning period.
[b]Total radiation assuming spherical symmetry.
[c]Net heat of combustion of 18,500 Btu/lb (4.3×10^7 j/Kg) assumed for all fuels.

TABLE 3.16

Summary of Bench Scale Test Data for Jet A Type Base Fuels and for JP-4 Base Fuel

Property	JP-5 Liquid	JP-8 Liquid	JP-4 Liquid
Yield Stress dynes/cm^2	-	-	-
Min.AIT, °C/°F	224/435	224/435	229/445
Flash Point, °C/°F	65/149	47/116	-18/0
Vapor Pressure at 37.8°C/100°F, Pa/psi	1103/0.16 at 30 minutes	1862/0.27 at 30 minutes	3447/0.50 at 2.5 minutes
Self-Spread Rate m/sec / in/sec	>1.27/>50	>1.27/>50	>1.27/>50
Burning Rate m/min / in/min	2.0×10^3/0.08	1.8×10^3/0/07	2.0×10^{-3}/0.08
Flame Spread Rate m/sec / ft/sec	<3.0×10^{-3}/<0.01	<3.0×10^{-3}/<0.01	2.22/7.3
Fireball size and radiation intensity under impact conditions (70° ± 10°F)			
W_{max}, m / W_{max}, ft (<1 sec)	2.9/9.5	-	5.8/19
W_{max}, m / W_{max}, ft (<10 sec)	2.9/9.5	-	5.8/19
W_{max}, m / W_{max}, ft (<10 sec)	1.1/3.6	-	3.5/11.5
Q_{max}, W/m^2 / Q_{max}, W/ft^2 (<10 sec)	506/47	-	40/427 < 1 sec 46/500 <10 sec

At the present time, there is significant research being carried out both in the UK and in the US and a collaborative program between the UK and US is currently being planned and discussed. Anti-misting fuels are discussed in more detail in Sections 4 and 5 of this report.

3.5.8 Flame Propagation and Burning Rates

The rate of flame spread across the surface of a pool of liquid or a solid is obviously an important factor in determining fire intensity, or at least the rate at which a fire can change from one of small size and intensity to one which is very large-exhibiting maximum severity and hazard.

In the case of liquid pools there is a very dramatic effect of fuel volatility. At temperature below the flash point of the liquid, the rate of flame spread is of the order of 60 m/min., whereas at temperatures above the flash point of the liquid, flame spreading rates ranging from 750 to 2250 m/min. are indicated (Coordinating Research Council[134]).

In the case of flame propagation across pools of liquid at temperatures below the flash point of the liquid (Glassman and Hansel[107] and MacKinven, Hansel and Glassman[135]) detailed laboratory studies on pure fuel samples have contributed significantly to an understanding of the mechanisms involved in the rate of flame speed. However, for most of the liquids of interest in aircraft fire safety considerations, such detailed laboratory measurements have not been performed. The tests themselves, although giving reproducible measurements for the pure fuel samples, are not readily translatable to the relative risk involved in various fuel spill accidents.

Generally, the situations involved in aircraft accidents will result in conditions where fuel spills do not result in the quiescent conditons used in the above-mentioned laboratory investigations, but rather result in various degrees of fuel dispersion involving drips, streams, misting, and atomization. In the literature, there have been attempts to conduct tests for these various fuel dispersion modes, but most of the tests yield only a relative ranking of various fuels, information that is difficult to use for quantitative risk assessment.

In the case of combustible solids, flame spread rates are significantly lower than in the case of combustible liquids (Kuchta[110]) and are influenced by a variety of factors including loading density, orientation of burning and size of fire. Hilado[106] presents a good summary of the many tests available for flame spreading rates over solids and the recent publication of the National Academy of Sciences[109] reaches important conclusions regarding appropriate test methods and proposed modifications for flammability tests for solids used in aircraft interiors, e.g., the recommendation that "the vertical test should be employed for all cabin and cargo compartment interior fabric materials...further, three separate tests, using flame application time of 3, 12, and 60 seconds should be employed in the vertical test."

3.6 Subgroup II - Conclusions and Recommendations

On the basis of a survey of aircraft materials fire hazards, the following recommendations are made:

3.6.1 General

There is a need to reexamine the entire problem of laboratory testing and material rating and selection and the evaluation of material and design changes on the full-scale fire hazards. On the basis of statistical studies of full-scale fires and scenarios derived from full-scale fires, the needs and characteristics of sub-scale and laboratory scale tests should be defined. Sub-scale or prototype and laboratory tests should be devised which meet these needs. Wherever possible these tests should be accompanied by analyses which provide for extension of the test data to the full-scale problem. "Reliable risk assessment methods have not been developed and systematically applied. Development of generalized fire scenarios to be used in analysis and development of fire prevention and control methods should be undertaken and given a high priority."[109]

"Better test methods for evaluation of fire resistance of materials are needed, particularly in simulating dynamic fire growth and full-scale real fires."[109] It is impossible to find totally safe materials. "Methods for risk and trade-off analysis must be developed and employed in materials selection."[109]

3.6.2 Specific

3.6.2.1 Thermal Ignition

It is recognized that the ultimate test for evaluation of the fire hazard associated with the thermal ignition of aircraft fluids is the full-scale aircraft itself. Some full-scale testing must be done to establish realistic parameters. Large,

sub-scale tests using realistic air flows and related environmental conditions provide an intermediate stage of evaluation. On a laboratory basis, tests using the uniformly heated, large (12 inch) sphere and the free convection pipe test represent the minimum evaluation procedure.

The following recommendations with respect to thermal ignition tests are made:

(1) The uniformly heated sphere, pipe test, and a forced convection test using a flat surface should be established.

(2) Analytical models should be developed describing each test and providing a bridge between the tests and between them and full-scale experience.

3.6.2.2 Spark Ignition

Electric Sparks - It must be recognized that, in most cases, the electric spark energies are sufficient to produce ignition of flammable gases and vapors. If a reduction in fire hazard is to be achieved with respect to electric spark ignition, research is needed: (a) to try to contain the fuel or at least reduce the generation of fuel vapor, mists and sprays; (b) to improve the isolation of electrical equipment and fuel even under failure modes; and (c) to minimize the break-up of fluid system components thus minimizing fluid release.

Static Electricity - Research is needed to obtain a better understanding of the mechanisms of electrostatic charge generation and spark formation.

Where fire suppression foams are used, attention should be given to these as factors in static charge generation.

Research should continue on entry system design and filling procedures to avoid charge generation during initial stages of tank filling; systems under development should be evaluated for their charging tendencies.

The use of conductivity improver in the fuel should be adopted to reduce the static hazard.

Friction Sparks - Friction sparks represent an important ignition source in aircraft crashes. Unless some new information becomes available, test method development in this area is given a low priority. There is a need to find methods of reducing the sparking tendency of practical metals, but no obvious suggestions can be made at this time.

Atmospheric Electricity (Lightning) - There is a need for continued work on the simulation of lightning strikes to typical current and new aircraft materials and construction configurations.

3.6.2.3 Cabin Materials

A comprehensive study of cabin materials fire hazards is reported in the NMAB study.[109] Many conclusions and recommendations were made with respect to specific materials. These are not repeated here. In general, we concur with their conclusions and recommendations. Some of their general recommendations and those related to laboratory testing are summarized below along with our recommendations.

(1) Methods for risk and trade-off analysis be developed and employed in materials selection.

(2) More meaningful flammability tests and methods for evaluation be developed to assist in materials development choice.

(3) Tests and guidelines for definition of toxic hazards from pyrolysis and combustion of polymeric materials be developed.

(4) The toxic hazard from pyrolysis and combustion products of the polymeric materials used in aircraft interiors be defined.

(5) Knowledge of the relationships of polymer structure and fire environments to the nature of pyrolysis and combustion products of polymers and combinations of materials be increased.

(6) The contribution of emergency oxygen systems to the potential fire hazard of polymeric materials be defined.

(7) Research be initiated to correlate test methods with fire hazard of polymeric interior cabin materials. Additional large-scale testing is required to provide the data base for validating small-scale tests.

(8) ASTM E-162, the radiant panel test, should be employed to determine the "flame resistance" of cabin and cargo compartment interior materials, since it more closely represents real conditions than do currently employed tests.

(9) The vertical test should be employed for all cabin and cargo compartment interior fabric materials. Then the same level of fire resistance would be maintained for all fabric materials. Further, three separate tests, using flame application time of 3, 12, and 60 seconds should be employed in the vertical test.

(10) Performance levels for acceptance in both the E-162 and vertical tests should be based on the responses of these materials in large-scale tests.

(11) The NBS smoke density test (NFPA 258) is the most useful smoke standard for interior cabin materials. The variation of smoke production with heat flux should be evaluated.

(12) It should be possible to evaluate toxicity by means of experiments with animals. These would include a measure of the incapacitation time and of the degree of toxicity. A simple procedure accessible to all laboratories should be developed. One of the aims is to find a correlation between the physico-chemical data of combustion gases and the incapacitation and intoxication of laboratory animals.

(13) The requirements contained in the regulations on the flammability of aircraft cabin materials should be reinforced; the materials, and a large number of the materials used in aircraft cabins, should be subject to more extensive study (especially flexible materials). In all cases, where there is no problem of obtaining the material, these should be studied more intensively, without respect to their location in the aircraft.

(14) Tests to determine the fire characteristics of materials should be developed which would measure their thermal properties (microcalorimetry) and try to evaluate them under conditions of temperature that are close to those which one finds in a fire - (vertical panels in a heated chamber).

(15) Sub-scale and full-scale tests for the qualification of materials are indispensable; the sub-scale tests, less difficult to do, should be undertaken before the full-scale tests, which are more expensive. One of their objectives is to find a correlation with laboratory tests, intended as a regulation test.

(16) The decorative PVF coatings are generators of smoke and toxic gas in the event of a fire. Research should be conducted for their replacement by a less critical material. The same for flexible polyurethane foams which represent a real danger from "flashover" in certain cases.

3.7 Figures

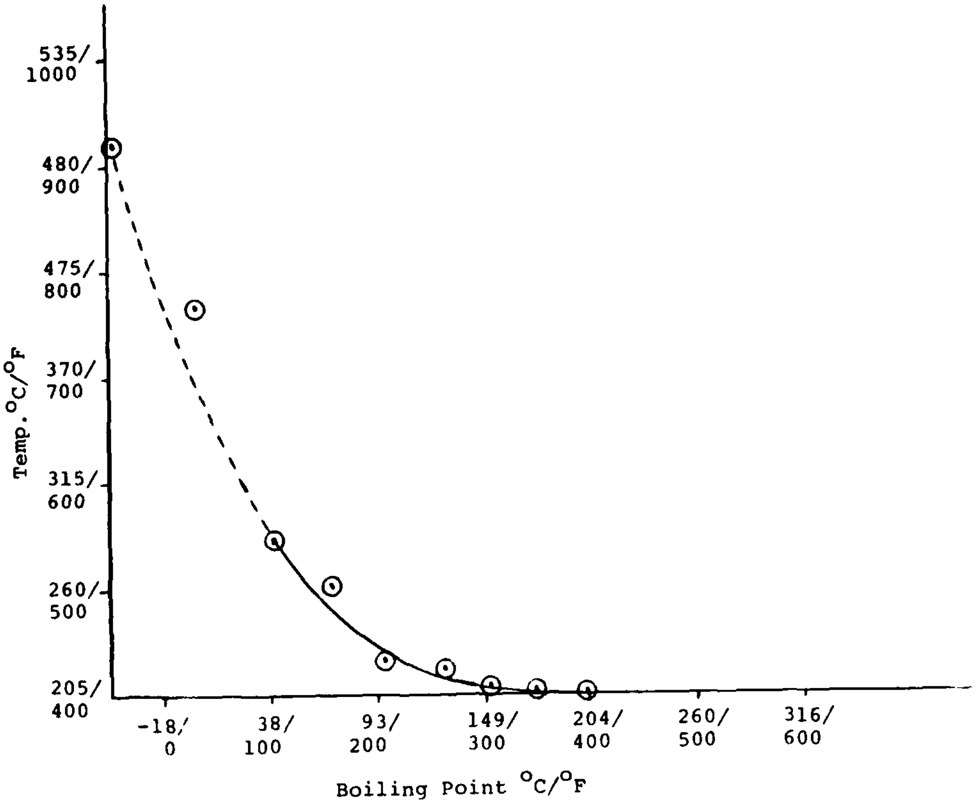


Figure 3.7.1 - Variation of Ignition Temperature With Boiling Point for Several Normal Aliphatic Hydrocarbons

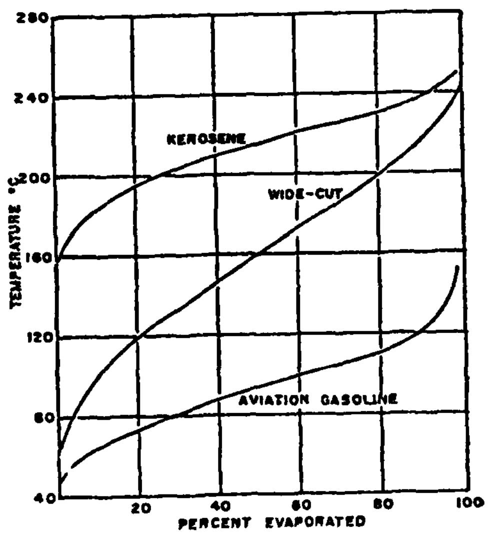


Figure 3.7.2 - Typical Distillation Curves of Aviation Fuels

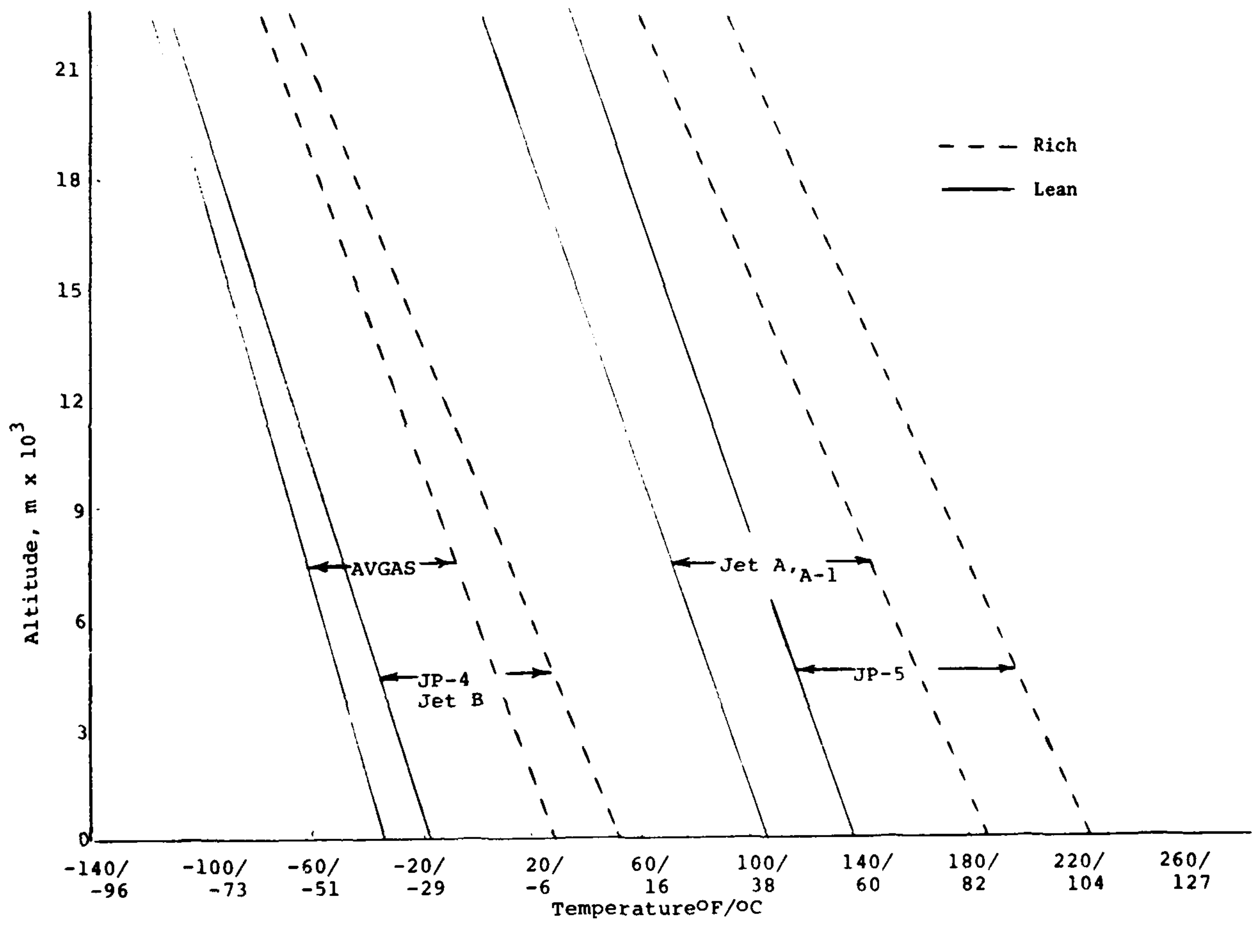


Figure 3.7.3 - Fuels Flammability Limits Versus Altitude

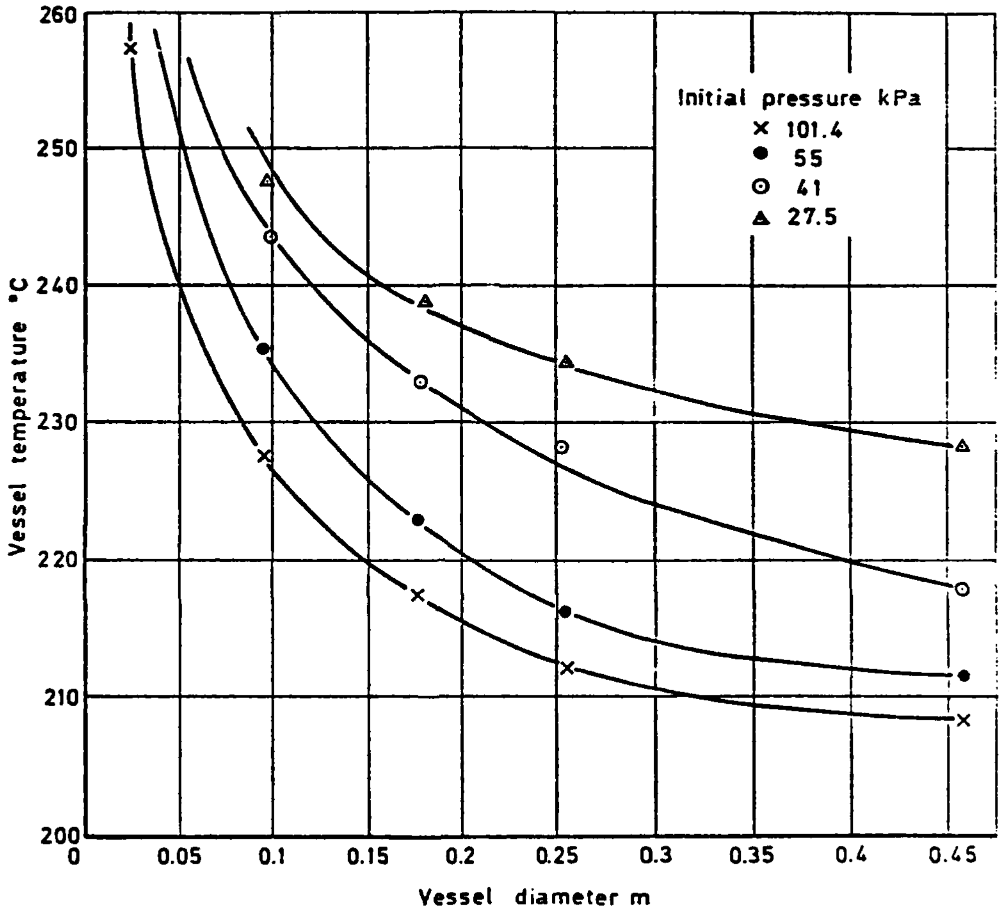


Figure 3.7.4 - The Effect of Vessel Size and Pressure on the Minimum Spontaneous Ignition Temperature of AVTUR Vapor

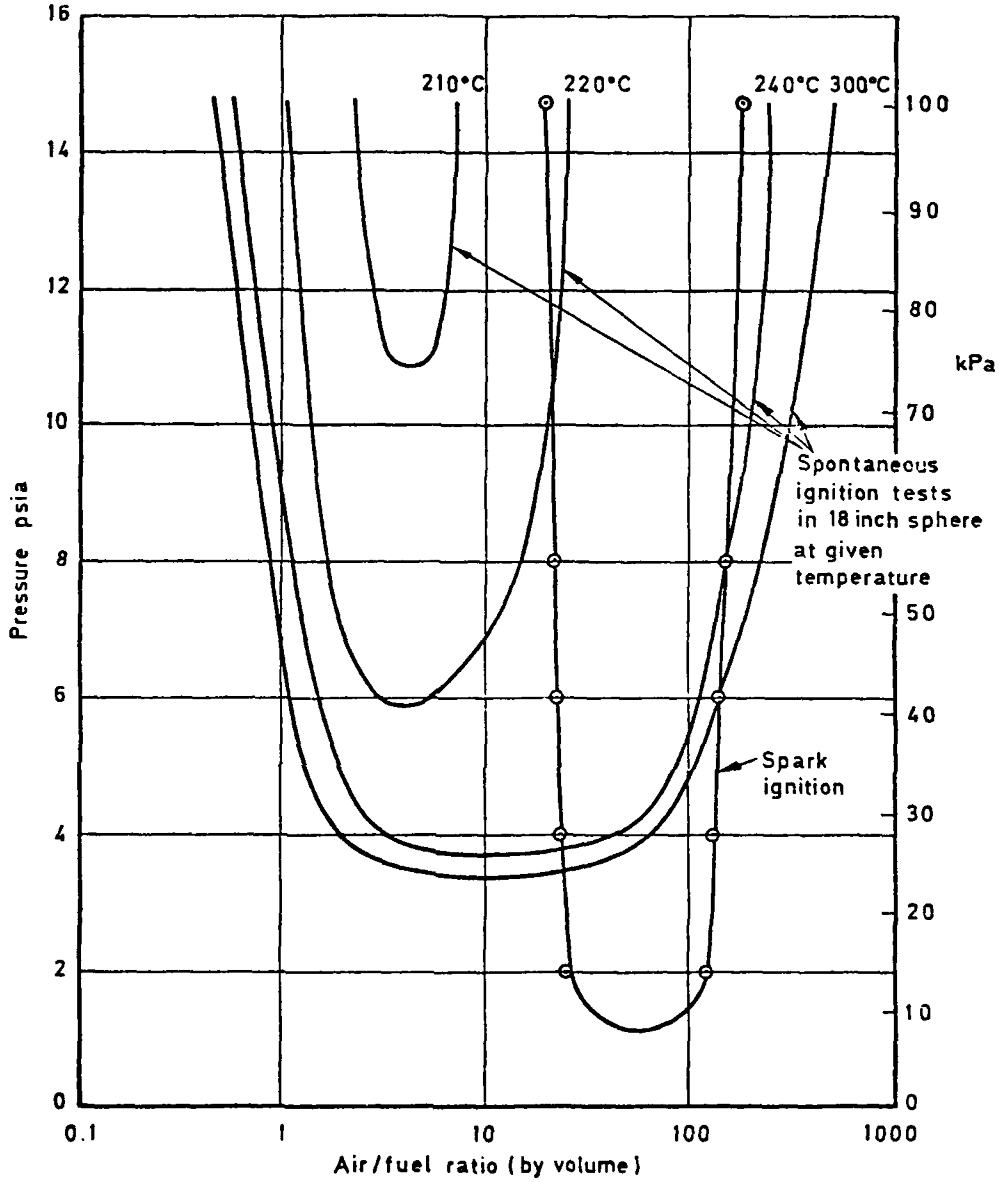


Figure 3.7.5 - Spark and Spontaneous Ignition Limits for AVTUR

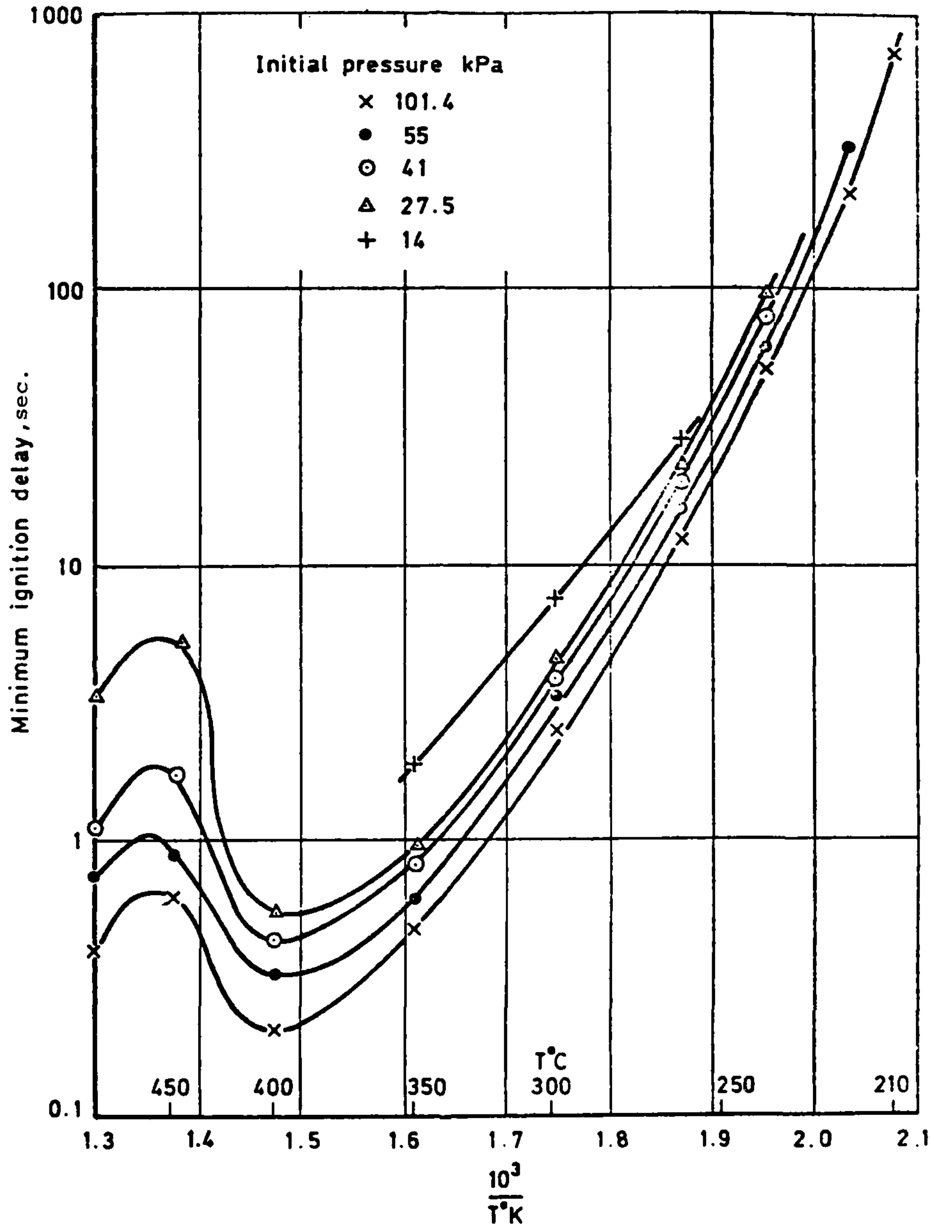


Figure 3.7.6 - Minimum Ignition Delay of AVTUR Vapor at Optimum Fuel Concentration

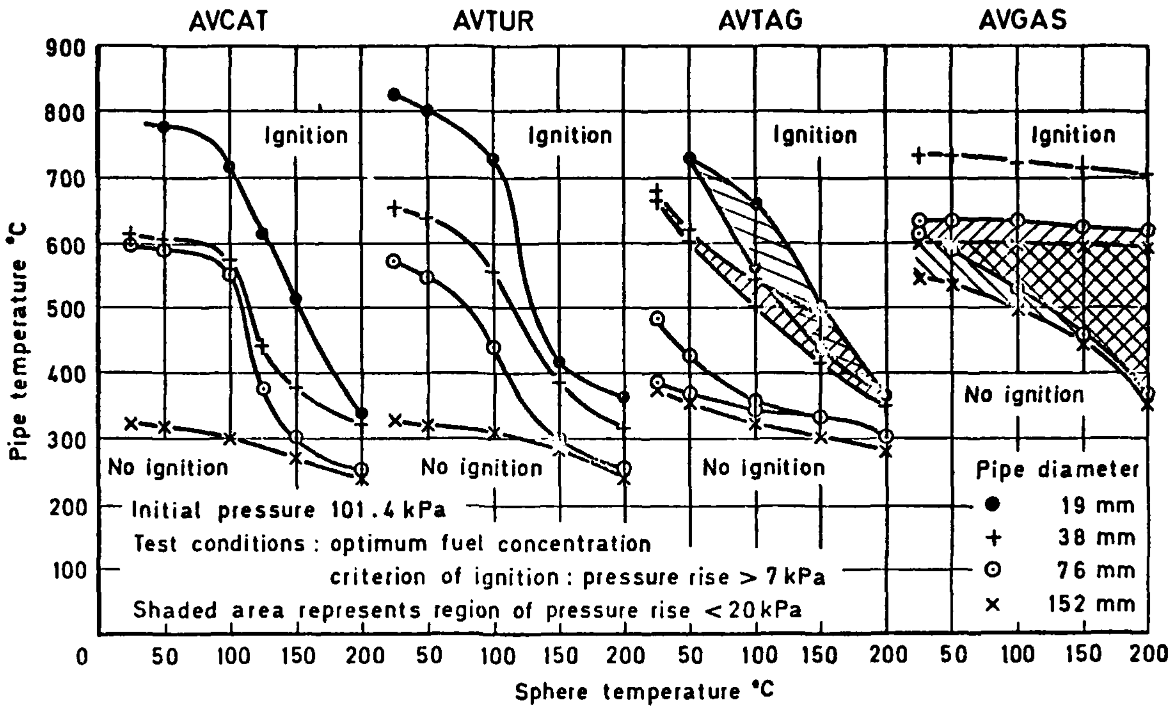


Figure 3.7.7 - Ignition Boundaries for Liquid Fuel on a Horizontal Hot Pipe in a 0.46 m Sphere

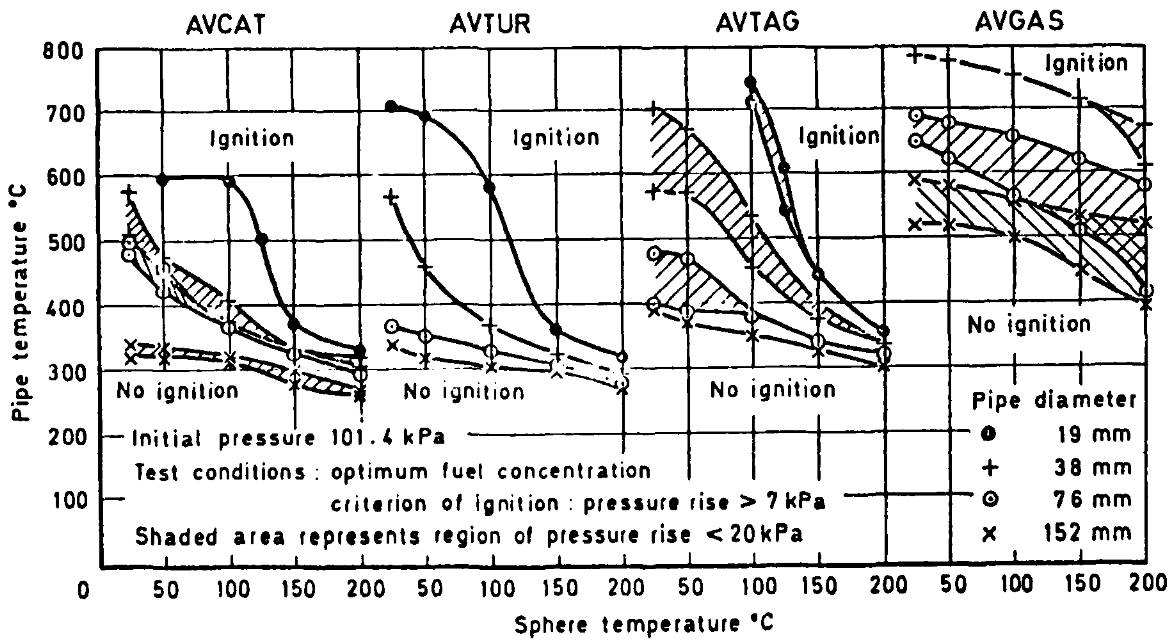


Figure 3.7.8 - Ignition Boundaries for Fuel Vapor on a Horizontal Hot Pipe in a 0.46 m Sphere

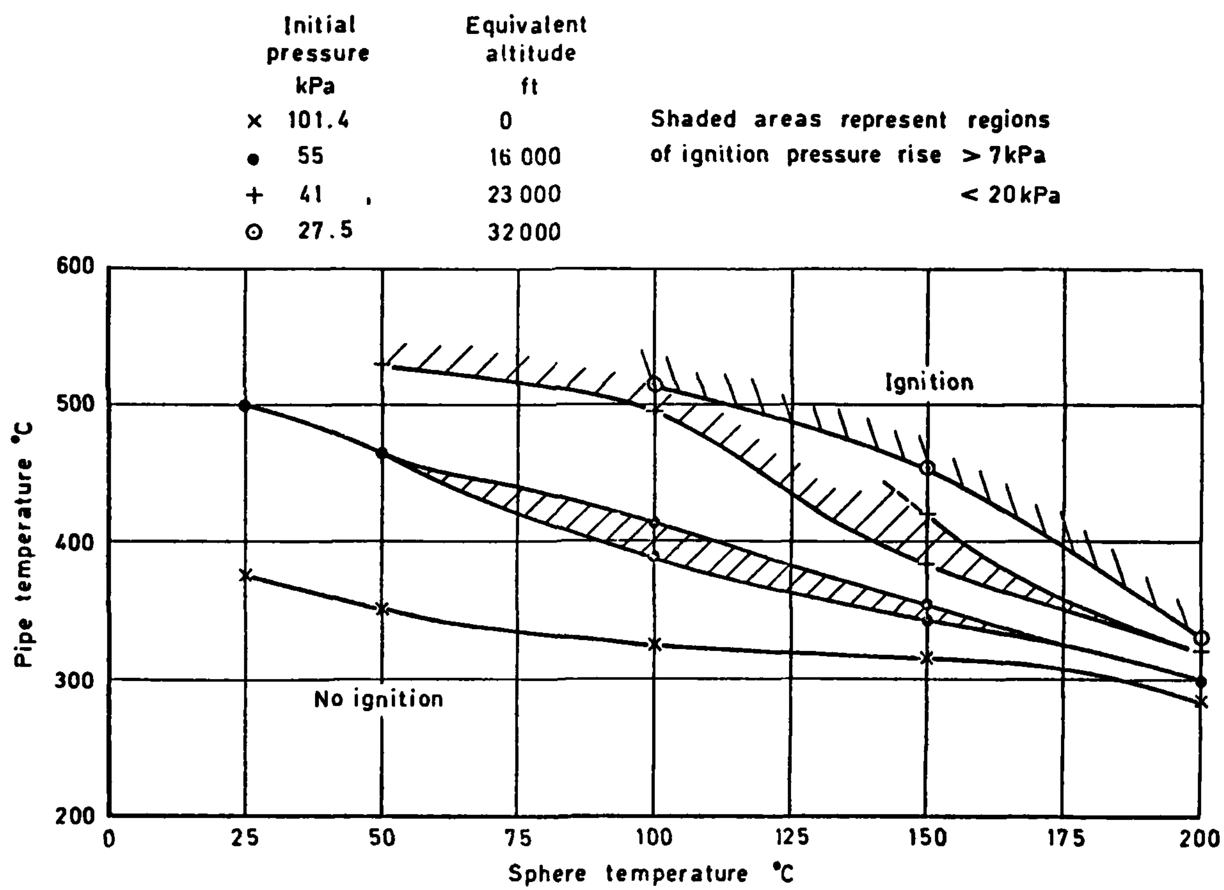


Figure 3.7.9 - Effect of Initial Pressure on the Ignition of AVTUR Vapor by a 76mm Hot Pipe in a 0.46m Sphere

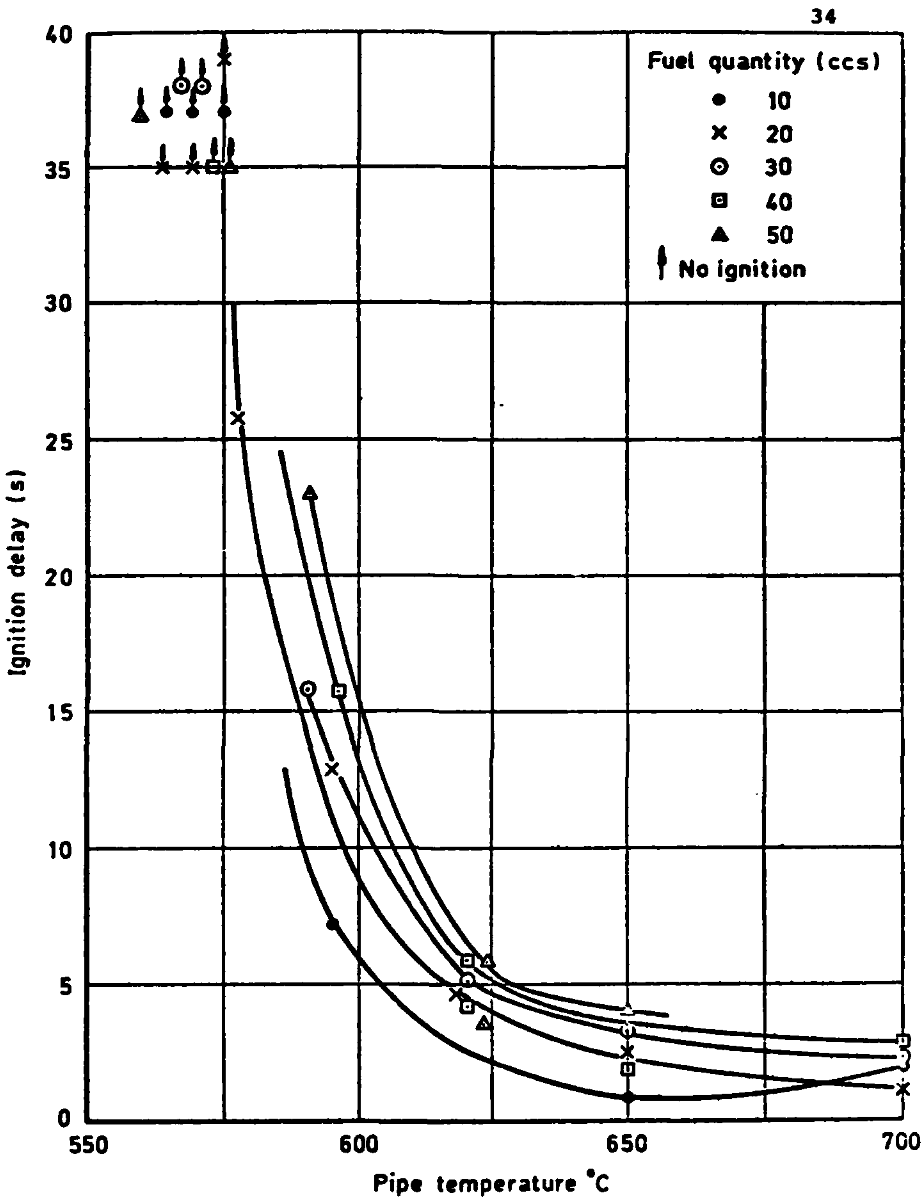


Figure 3.7.10 - Ignition Delay for AVTUR Liquid on a 76mm Pipe in an 0.46m Sphere

(Sphere Temperature 25°C)

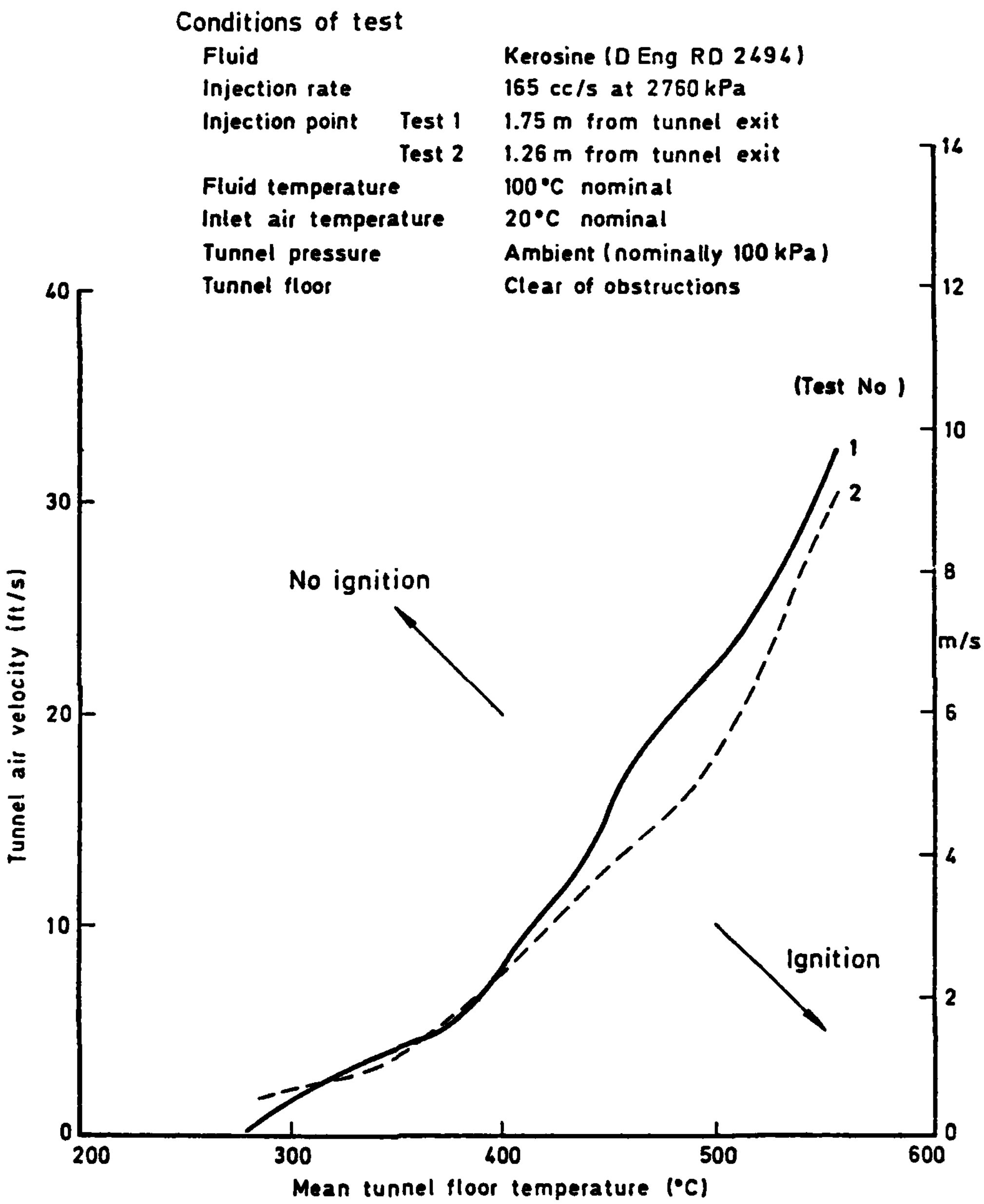


Figure 3.7.11 - Comparison of Typical Results to Demonstrate the Effect of Heated Floor Length

Spontaneous Ignition Research (Reference 21)

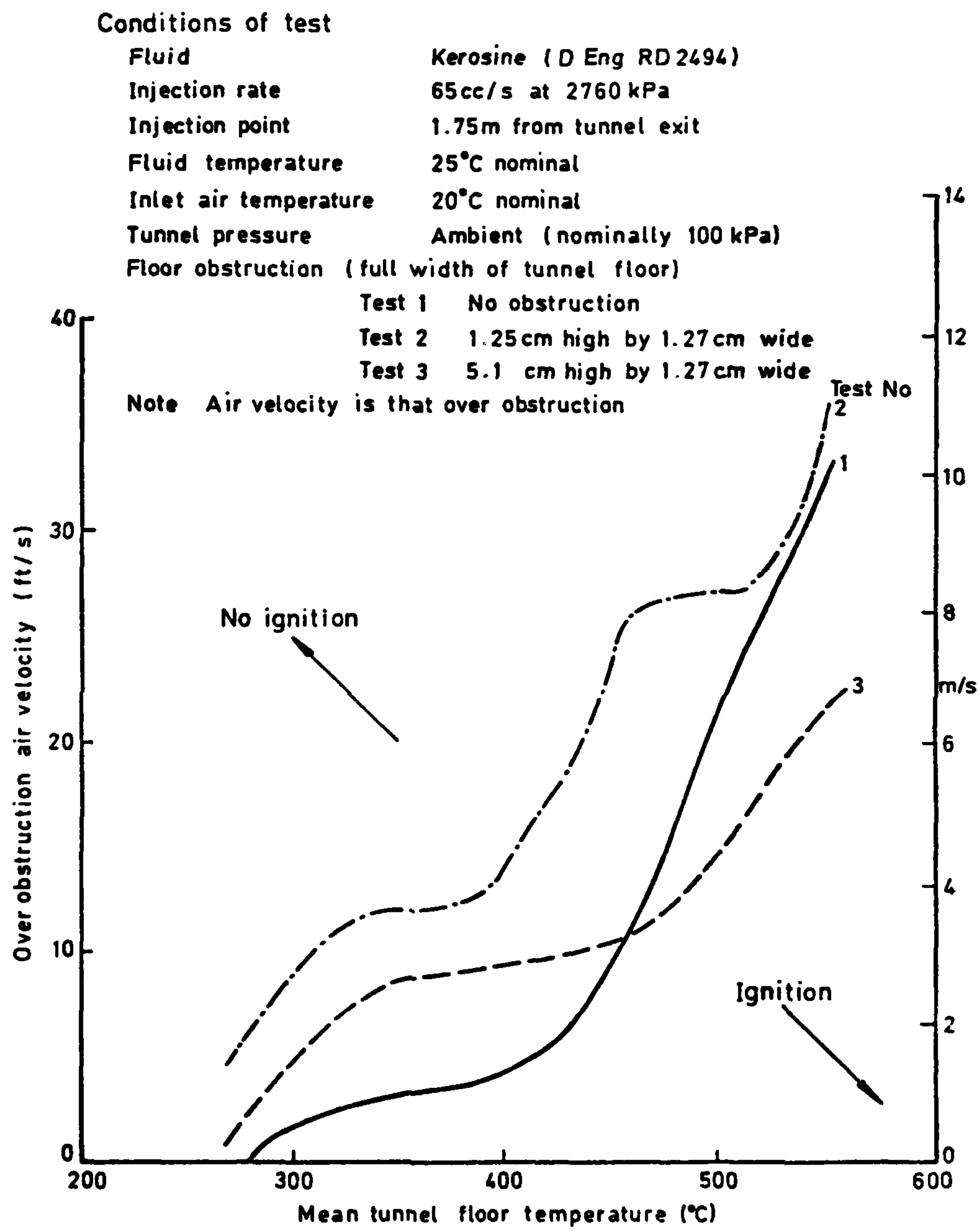


Figure 3.7.12 - Comparison of Typical Results to Demonstrate the Effect of Floor Obstructions

Spontaneous Ignition Research (Reference 21)

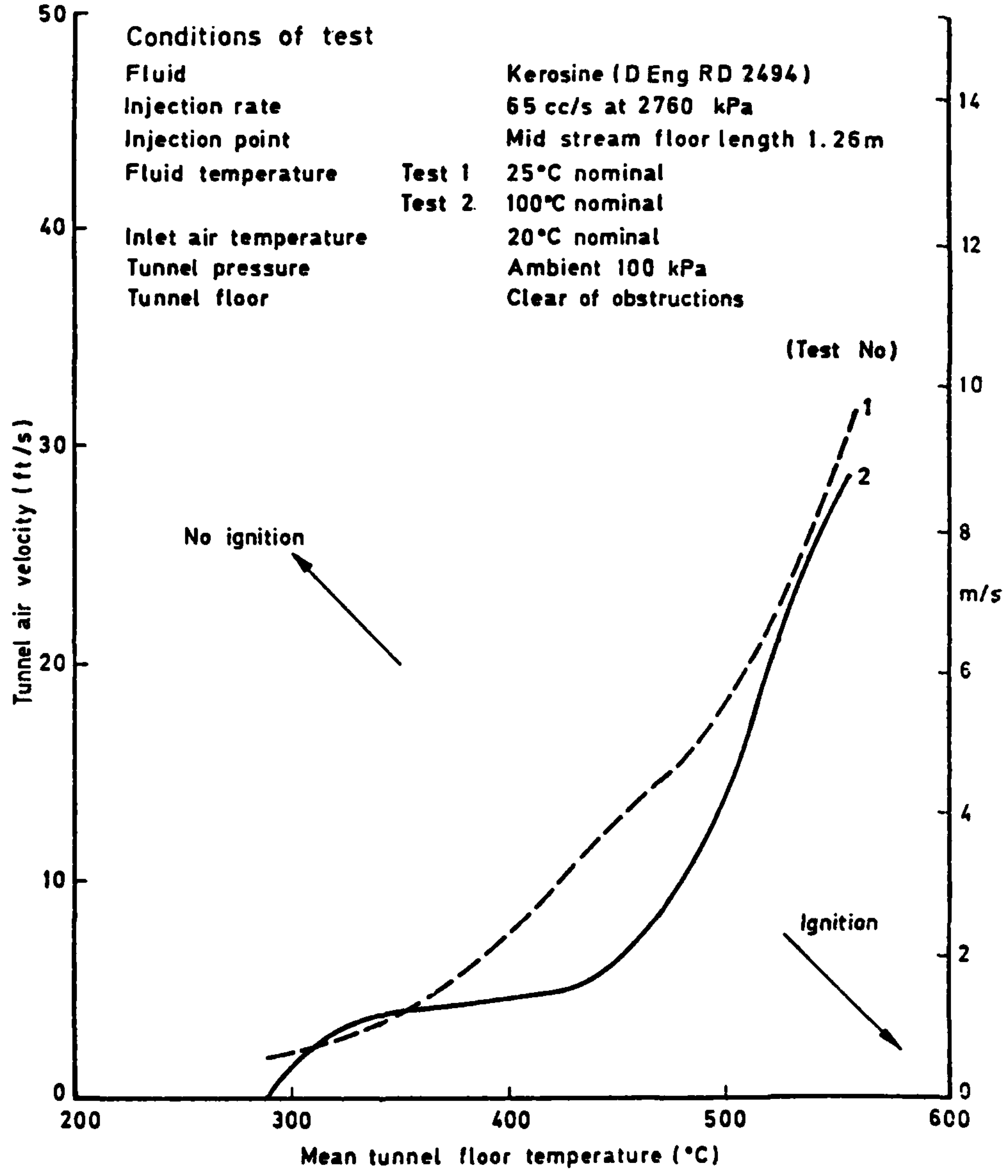


Figure 3.7.13 - Comparison of Typical Results to Demonstrate the Effect of Fuel Temperature

Spontaneous Ignition Research (Reference 21)

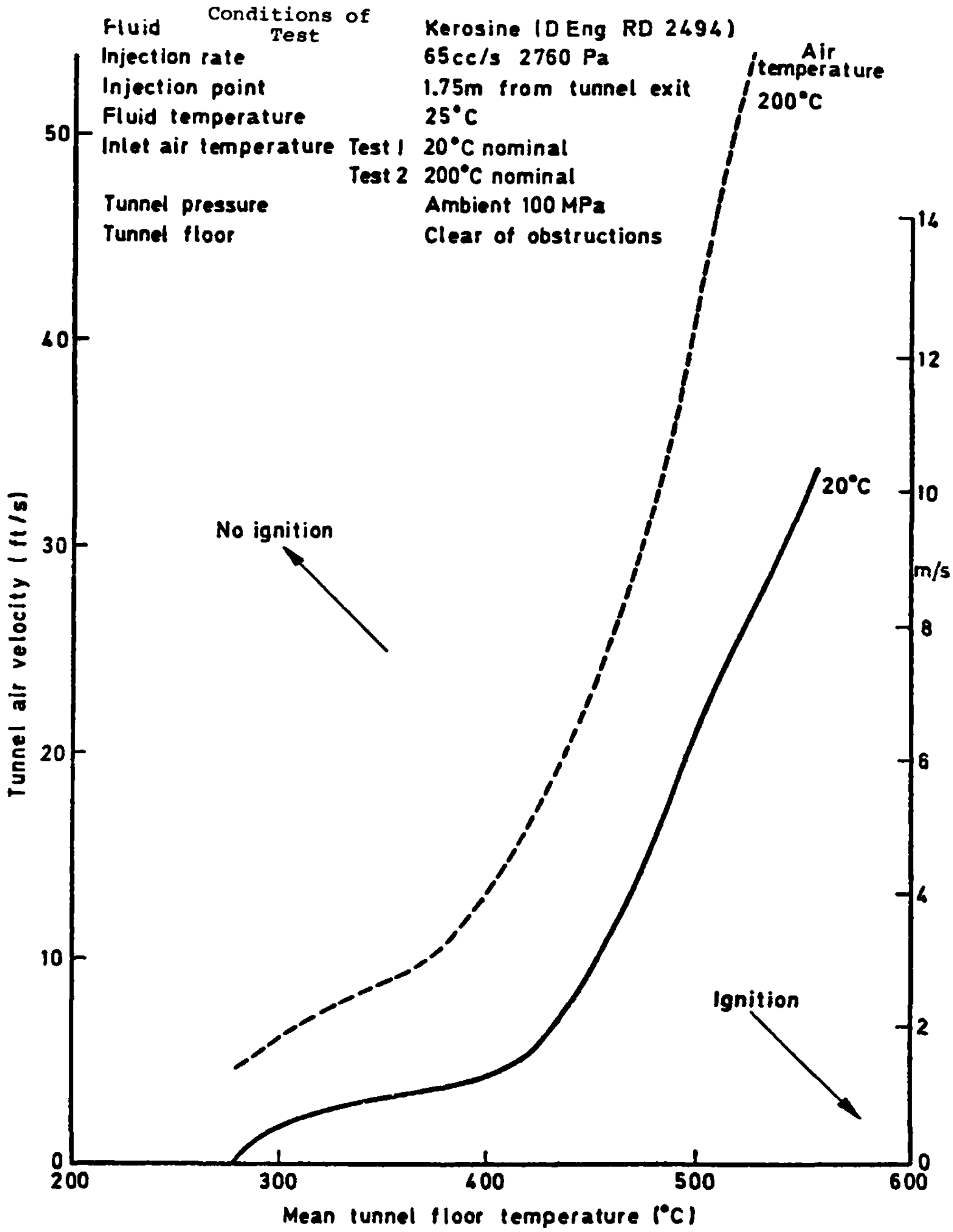


Figure 3.7.14 - Comparison of Typical Results to Demonstrate the Effect of Air Temperature

Spontaneous Ignition Research (Reference 21)

Conditions of test

Fluid		Kerosine (D Eng RD 2494)
Injection rate		65 cc/s at 2760 kPa
Injection point		1·2m from tunnel exit
Fluid temperature		25°C to 35°C
Inlet air temperature		20°C nominal
Tunnel pressure	Test 1	100 kPa nominal
	Test 2	180 kPa nominal
	Test 3	250 kPa nominal
	Test 4	55 kPa nominal
Tunnel floor		Clear of obstruction

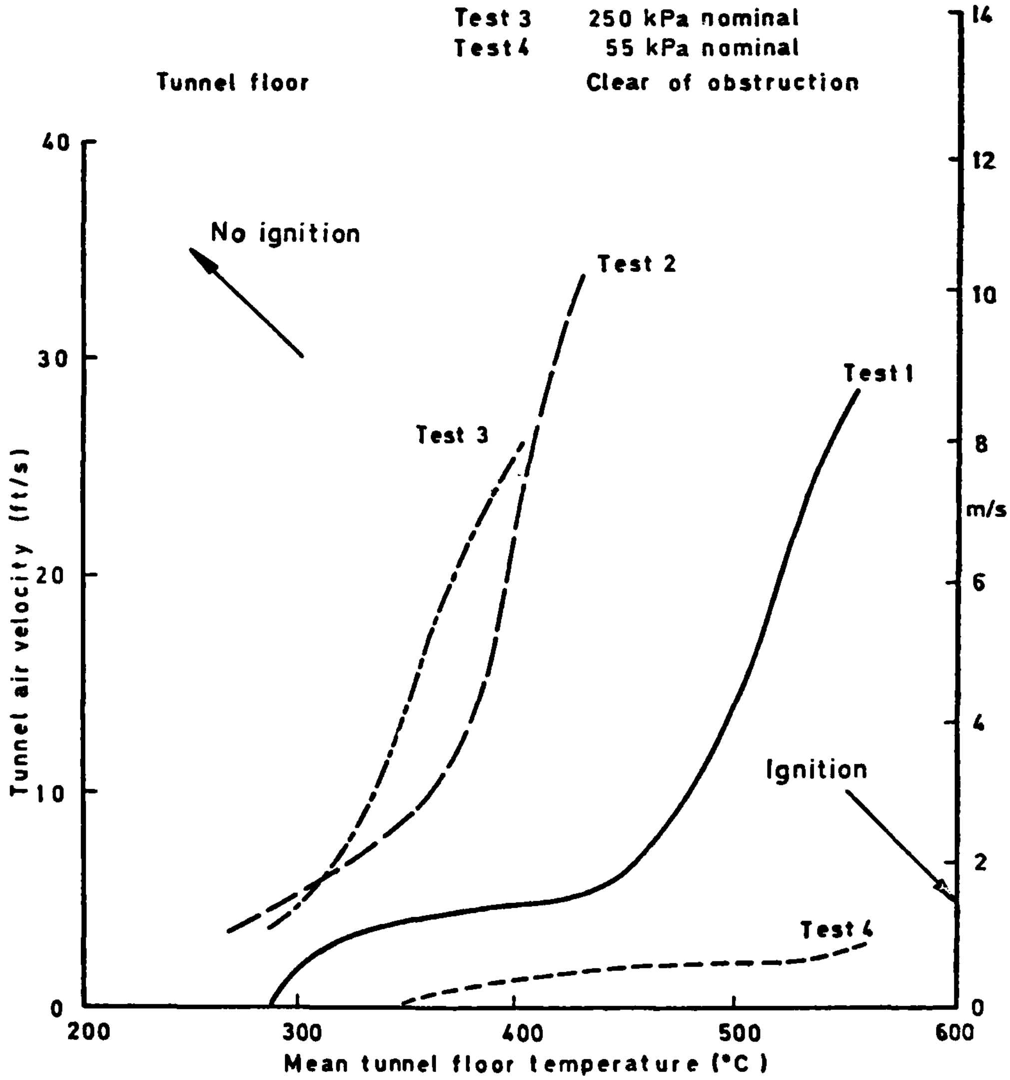


Figure 3.7.15 - Comparison of Typical Results to Demonstrate the Effect of Air Pressure

Spontaneous Ignition Research (Reference 21)

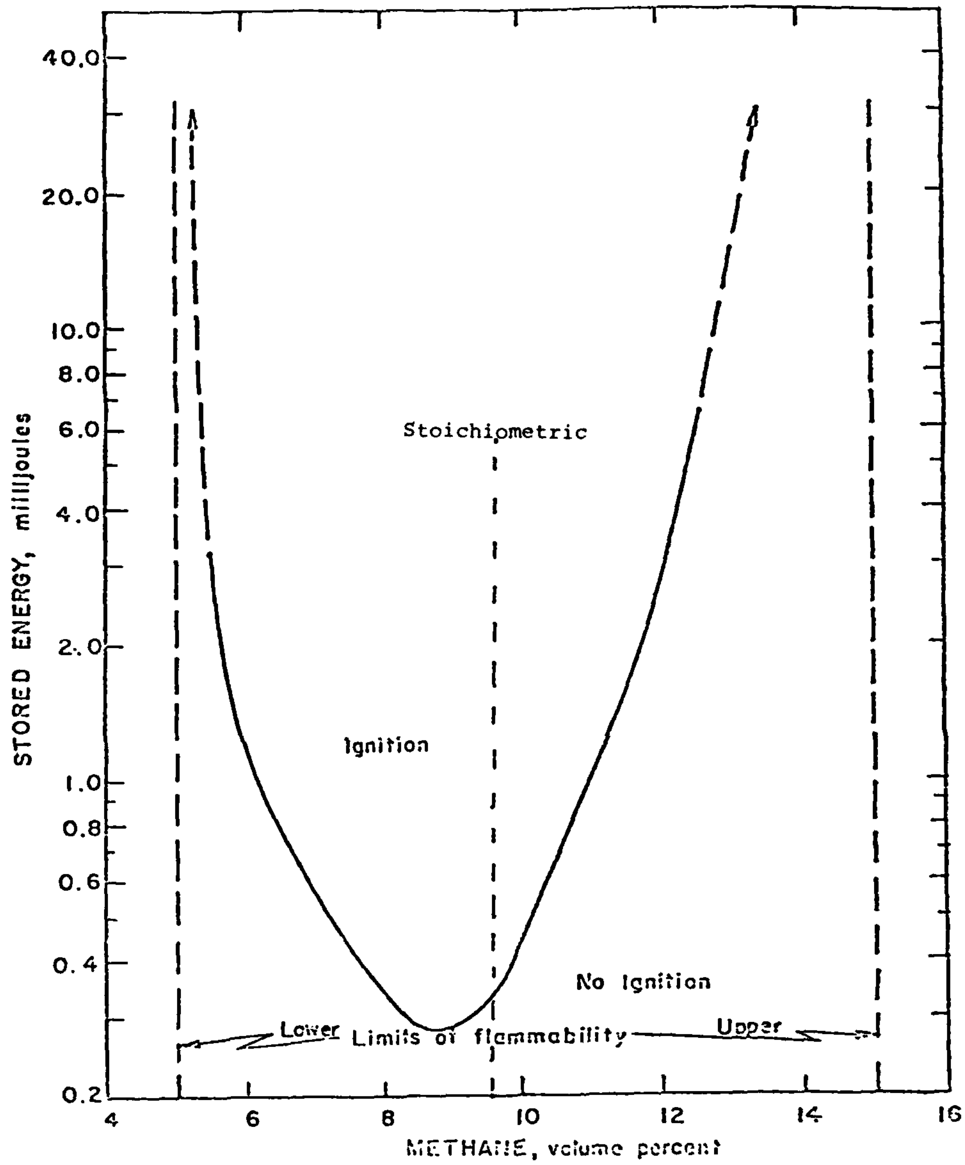


Figure 3.7.16 - Variation of Ignition Energy With Combustible Concentration for Methane in Air at Atmospheric Pressure (Reference 31)

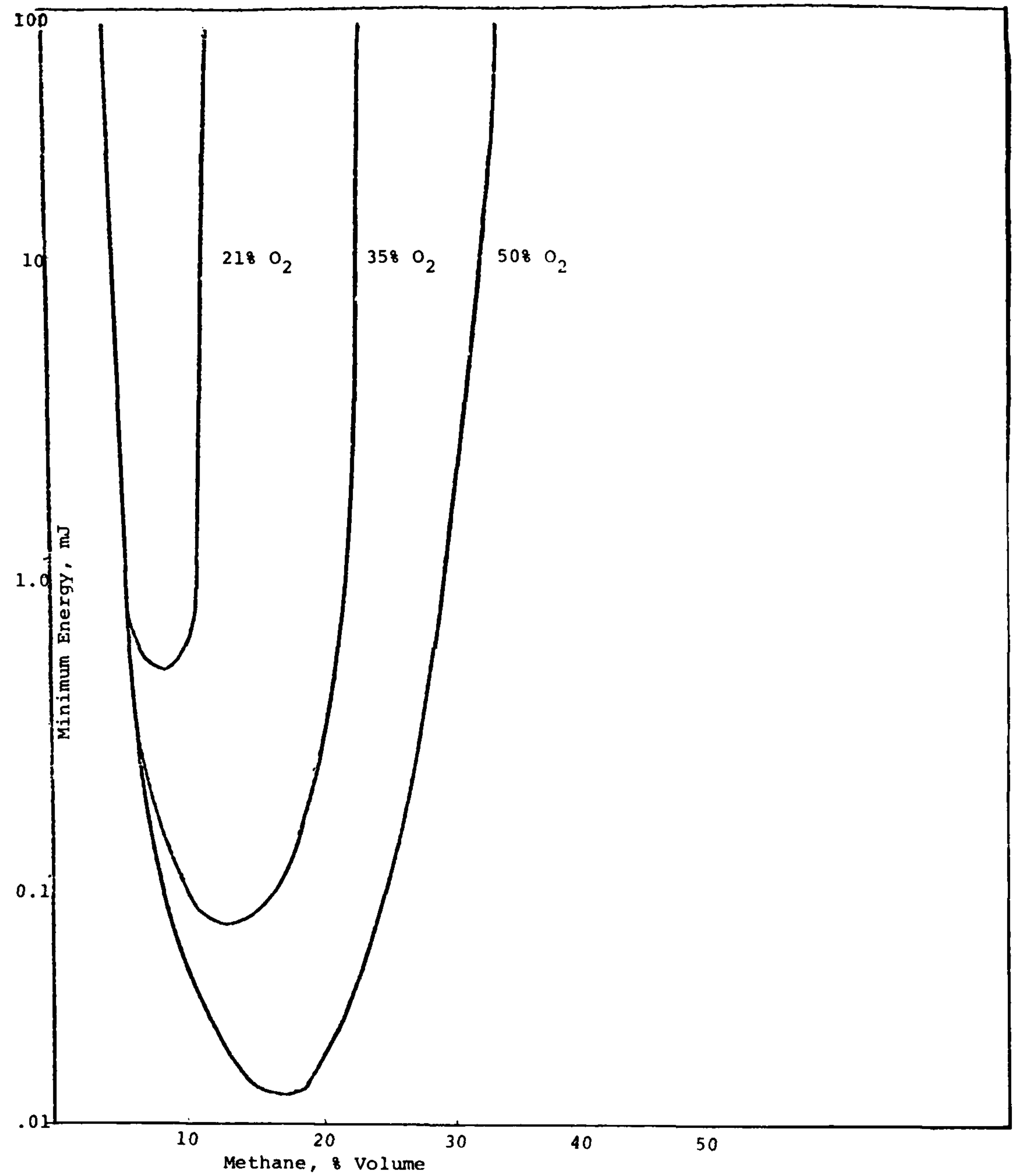


Figure 3.7.17 - Effect of O_2 Concentration on E_i

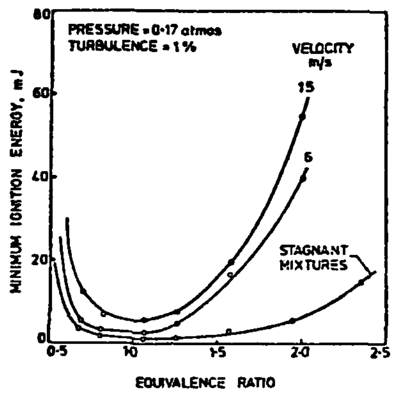


Figure 3.7.18 - Effect of Mixture Velocity on E_i min

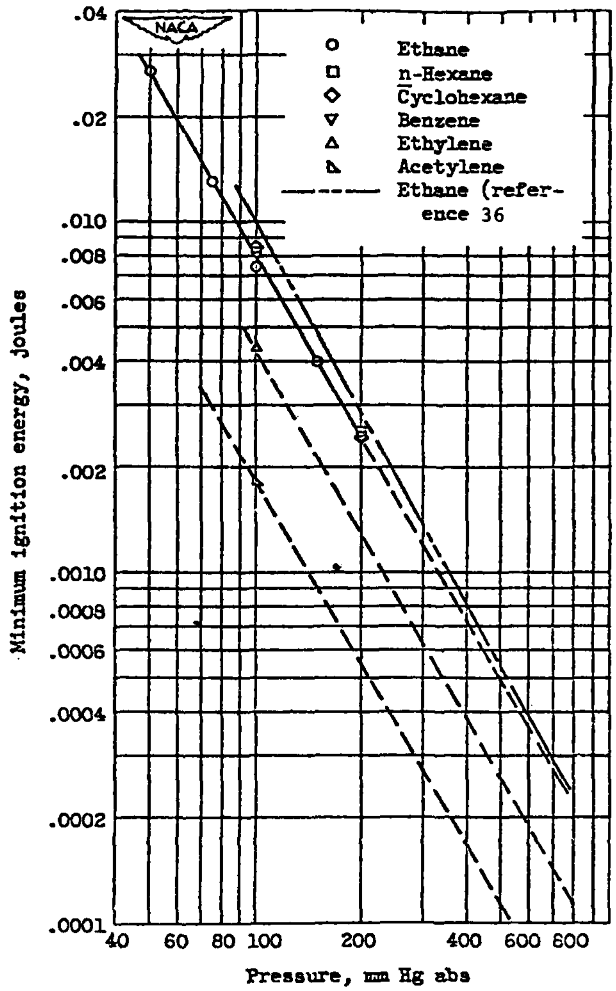


Figure 3.7.19 - Effect of Pressure on $E_i$min

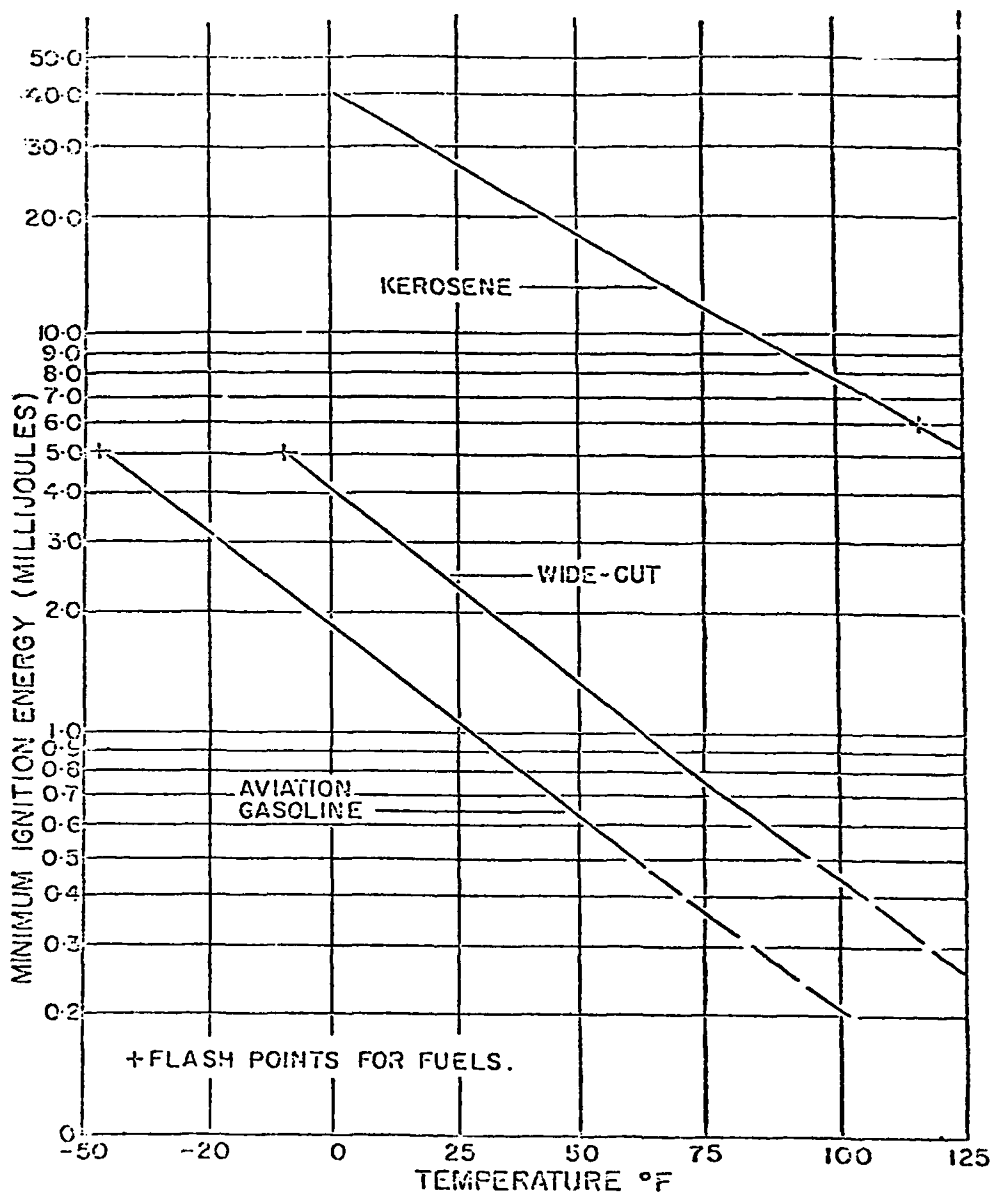


Figure 3.7.20 - Minimum Spark Ignition Energies for Fuel-Air Spray Mixtures (Reference 36)

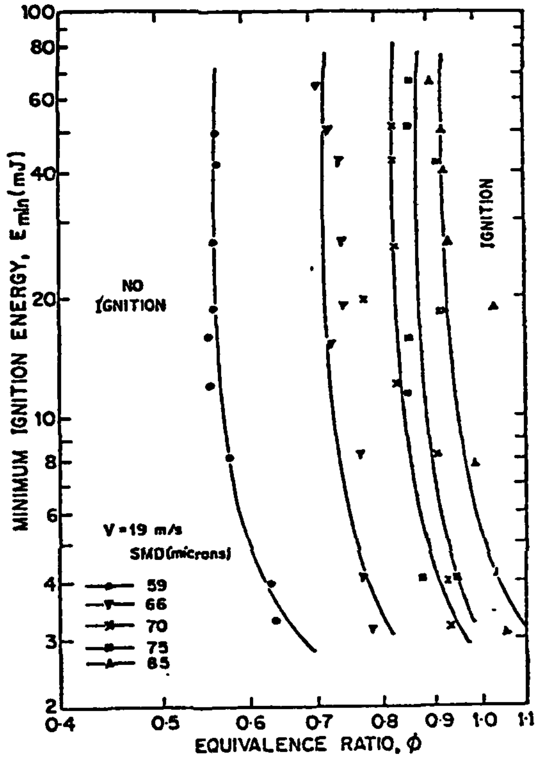
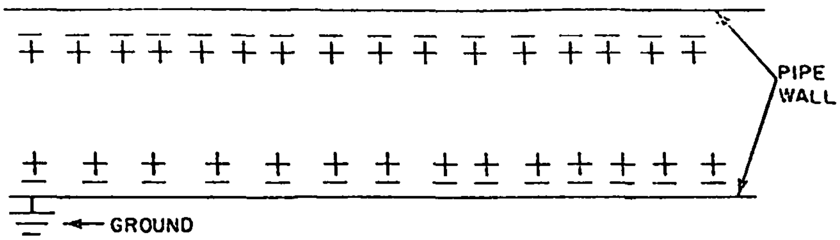
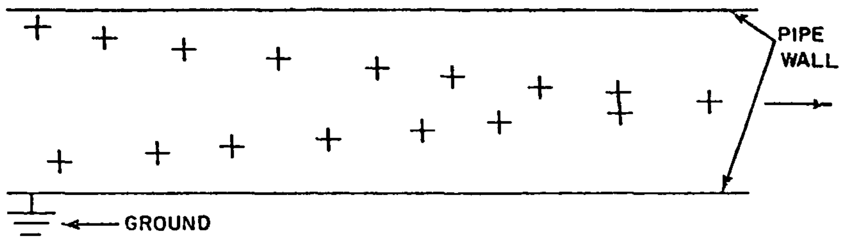


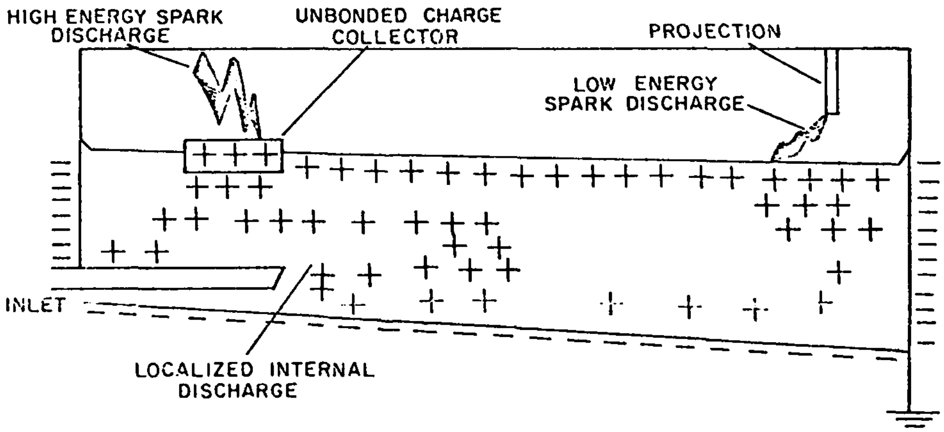
Figure 3.7.21 - Graphs Illustrating the Influence of Atomization Quality on Ignition Limits (Reference 37)



a) Fuel at Rest in a Pipe Showing Adsorption of Ionic Impurities at Pipe Wall



b) Separation of Charge as Fuel flows Through Pipe



c) Discharges Inside Tank

Figure 3.7.22 - Charge Generation and Discharge Mechanism

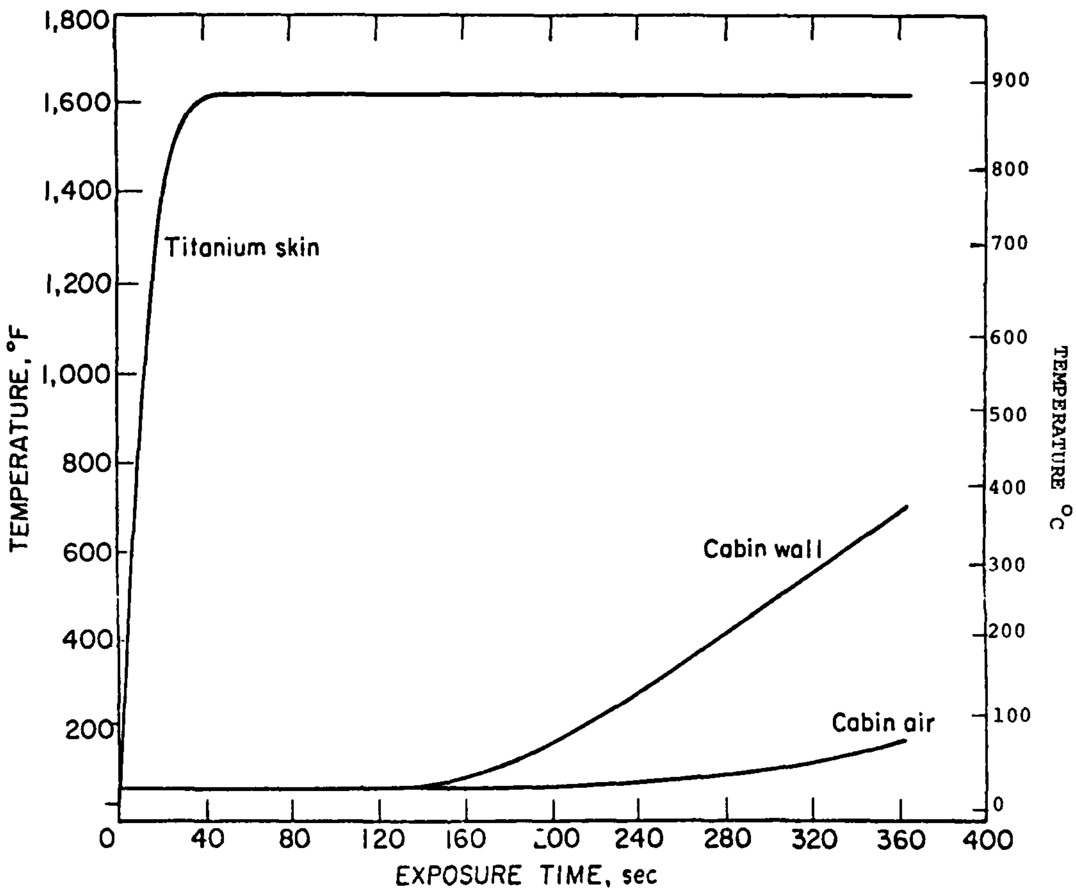


Figure 3.7.23 - Predicted Temperature History of a Titanium Fuselage Adjacent to a Severe External JP-4 Fuel Fire (Reference 110)

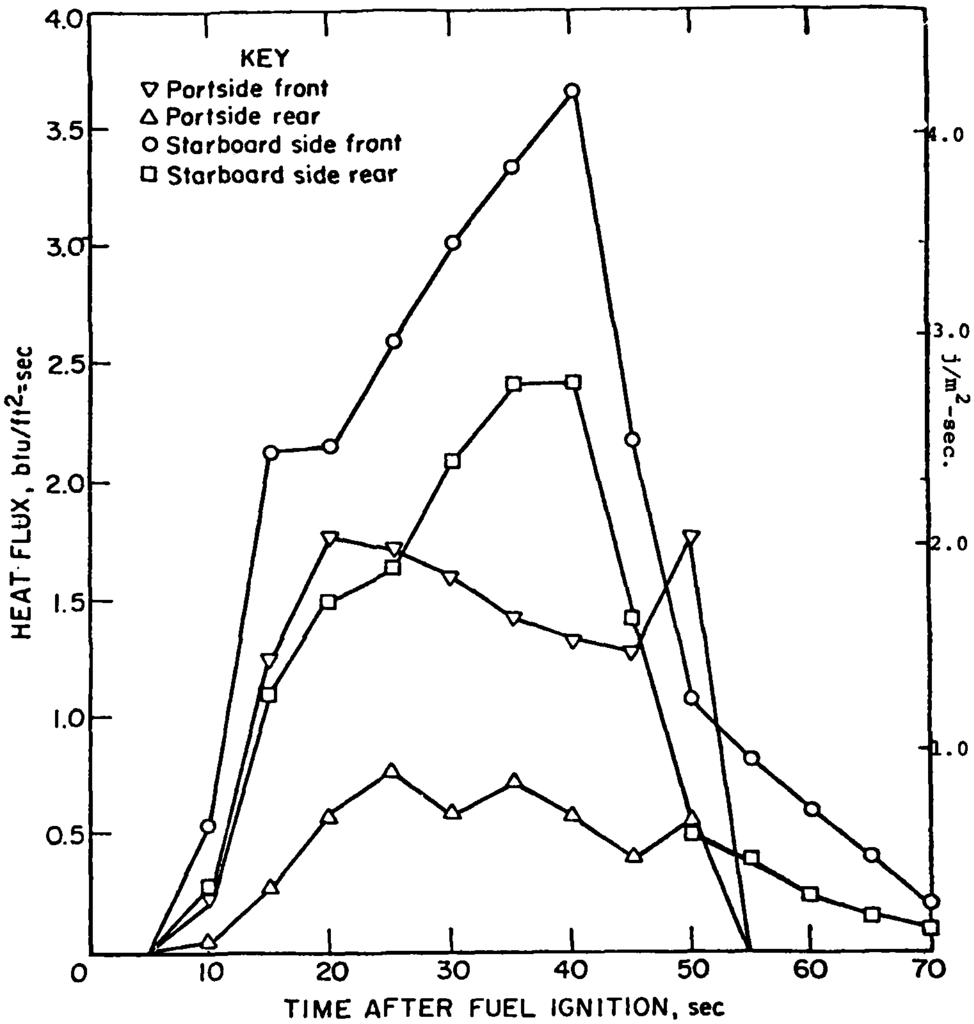


Figure 3.7.24 - Heat Flux Versus Time After Fuel Ignition in Full-Scale Fire Extinguishment Test Simulating an Engine Fire (JP-4) on a B-47 Aircraft. Geyer[112]

3.8 References

(1) Whyte and Gardner.

(2) Lydiard, W. G., "Fuel System Problems in High Speed Aircraft," Journal Royal Aeronautical Socity, L8 1124 (1964).

(3) Lydiard, W. G., White, R. G., and Winyard, A., "A Survey and Analysis of Aircraft Fire Statistics," RAE Technical Report 68046 (1968).

(4) Bowes, P. C. and Langford, B., "The Spontaneous Ignition of Oil-Soaked Lagging," Fire Research Station Note 665 (1967).

(5) Jost, W., Explosion and Combustion Processes in Gases, McGraw-Hill (1946).

(6) Semenov, N., Chemical Kinetics and Chain Reactions, Clarendon Press (1935).

(7) Macdonald, J. A. and White, R. G., "Spontaneous Ignition of Kerosene (Avtur) Fuel Vapor: the Effect of Vessel Size," RAE Technical Report 65138 (1965).

(8) Geib, E. R. and Bartsch, K. D., "Autogenous Ignition of Flammable B-70 Fluids," North American Aviation Inc., Report TFD-61-628 (1961).

(9) Stringer, F. W., Clarke, A. E., and Clarke, J. S., "The Spontaneous Ignition of Hydrocarqon Fuels in a Flowing System," 1 Mech (London) Symposium on Diesel Engine Combustion, Paper No. 20 (April 7-10, 1970).

(10) Perlee, H. E. and Zabetakis, M. G., "Compressor and Related Explosions," U.S. Department of the Interior, Bureau of Mines IC 8187 (1963).

(11) Shell Aviation News (January 1955).

(12) King, H. F. and Coil, J. A., "Hydraulic Fluids for Use in High Pressure Shipboard Equipment," ASTM Special Technical Publication No. 267 (1959).

(13) Zabetakis, M. G., Scott, G. S., and Kennedy, R. E., "Autoignition of Lubricants at elevated pressures," U.S. Department of the Interior, Bureau of Mines Rl 6112 (1962).

(14) Macdonald, J. A. and Cansdale, J. T., "Spontaneous Ignition of Aircraft Fuel," RAE Technical Report 72059 (1972).

(15) Lydiard, W. G. and Macdonald, J. A., "Design Aspects Relating to Aircraft Fires," Proceedings of the symposium held at the Fire Research Station, Boreham, Paper No. 8 (December 8, 1966).

(16) Macdonald, J. A. and Cansdale, J. T., "Spontaneous Ignition of Aircraft Hydraulic Fluids," RAE Technical Report 74066 (1974).

(17) Kuchta, J. M., Bartkowiak, A., Spolan, I., and Zabetakis, M. G., "Flammability Characteristics of High Temperature Hydrocarbon Fuels," Technical Documentary Report ASD-TDR-62-328, Directorate of Materials and Processes, Wright-Patterson Air Force Base, Ohio.

(18) Macdonald, J. A., "Ignition of Kerosene by Hot Pipes," RAE Technical Report 67162 (1967).

(19) Goodall, D. G. and Ingle, R., "Fire Resistance of Hydraulic Fluids," ASTM Special Technical Publication No. 406 (1966).

(20) Rae, D., Singh, B., and Dawson, R., "The Size and Temperature of a Hot Square in a Cold Flame Surface Necessary for Ignition of Methane," Ministry of Power, Safety in Mines Research Establishment, Research Report No. 224.

(21) Pickerall, R. H. and Beardsley, G., "Spontaneous Ignition and Flashback Ignition Research," Summary of Research Work and Safety Recommendations Installation Research Report IAR08204.

(22) Burrows, M. J., "Spontaneous Ignition Studies at Conditions Relevant to Supersonic Aircraft," Lucas Aerospace Co., Ltd., Report No. B49 (May 5, 1973).

(23) Lewis, B. and von Elbe, G., Combustion, Flames and Explosions of Gases, New York, Academic Press, (1951) pp 390-425.

(24) Blanc, M. V., Guest, P. G., von Elbe, G., and Lewis, B., "Ignition of Explosive Gas Mixtures by Electric Sparks. I. Minimum Ignition Energies and Quenching Distances of Mixtures of Methane, Oxygen and Inert Gases," J.Chem.Phys. 15 (1974) pp 798-802.

(25) Lewis, B., and von Elbe, G., "Ignition of Explosive Gas Mixtures by Electric Sparks. II. Theory of Propagation of Flame from an Instantaneous Point Source of Ignition," J.Chem.Phys. 15 (1947) pp 803-808.

(26) Blanc, M. C., Guest, P. G., von Elbe, G., and Lewis, G., Third Symposium on Comb-¬tion and Flame and Explosion Phenomena, Baltimore, Williams and Wilkins (1949) pp 363-367.

(27) Moorhouse, J., Williams, A., and Maddison, T. E., "An Investigation of the Minimum Ignition Energies of Some C_1 to C_7 Hydrocarbons," Combustion and Flame 23 (1974) pp 203-213.

(28) Metzler, A. J., National Advisory Committee for Aeronautics, "Minimum Ignition Energies of Six Pure Hydrocarbon Fuels of the C_2 and C_6 Series," (August 1952) NACA RM.E52 F27.

(29) Metzler, A. J., National Advisory Committee for Aeronautics, "Minimum Spark Ignition Energies of 12 Pure Fuels at Atmospheric and Reduced Pressure," (October 1953), NACA RM E53 H3.

(30) Calcote, H. F., et al "Spark Ignition - Effect of Molecular Structure," Ind.Eng.Chem.v44, n11, (1952) pp 2656-2660.

(31) Kuchta, J. M., et al, US Bureau of Mines, "Ignitability of Fuel Tank Atmospheres," (February 12, 1963) First Annual Report.

(32) Ross, K., Shell Research Ltd., Thornton Research Centre, "Air Release from Supersaturated Fuel," (January 1972) Report K195.

(33) Swett, C. C., Jr., National Advisory Committee for Aeronautics, "Spark Ignition of Flowing Gases," (1949), NACA RM E9E17.

(34) Ballal, D. R., and Lefebvre, A. H., 15th Symposium (International) on Combustion, London, The Combustion Institute, (1975) pp 1473-1481.

(35) Scull, W. E., National Advisory Committee for Aeronautics, "Relation Between Inflammables and Ignition Sources in Aircraft Environments," (1951) NACA Report 1019.

(36) Liebman, I., et al, "Ignition of Tank Atmospheres During Fuel Loading," Proceedings American Petroleum Institute, Section III - Refining (1965) pp 227.

(37) Rao, K. V. L. and Lefebvre, A. H., "Minimum Ignition Energies in Flowing Kerosene-Air Mixtures," Combustion and Flame 27 (1976) pp 1-20.

(38) Kester, F. L., et al, Dynamic Science Corp., "A Study of Aircraft Fire Hazards Related to Natural Electrical Phenomena," (June 1968) Final Report NASA-CR-1076.

(39) Schaufele, R. D., "Reducing Fire Hazards in Commercial Transport Aircraft," AGARD Conference Proceedings No. 212 (1976) pp 17-6.

(40) Gardner, L., National Research Council of Canada, "Jet Fuel Handling and Safety," (April 1976), DME/NAE Quarterly Bulletin No. 1976 (1).

(41) Coordinating Research Council, Inc., New York, "Generation and Dissipation of Electrostatic Charge During Aircraft Refueling - a Selected Literature Review," (March 1974) CRC Project CA-36-61.

(42) Backman, K. C., et al, Esso Research and Engineering Division, "Aircraft Incidents Attributed to Static Electricity, 1959-1964," (July 1969) Report No. RL-45M-69.

(43) Coordinating Research Council, Inc., New York, "Electrostatic Discharges in Aircraft Fuel Systems," (Phase I, April 1960) CRC Project No. CA-6-58, (Phase II, July 1961) CRC Project No. CA-22-59.

(44) Bruinzeel, C., "Electric Discharges During Simulated Aircraft Fueling," J.Inst.Petrol. v49, n473 (May 1963) pp 125-139.

(45) Gardner, L., "The Generation of Static Electricity During Aircraft Refueling," Can.Aeronaut. Space J. 10 (1964) pp 193-202.

(46) Hemke, H. P. Boeing Co., "Fuel Tank Explosions and Minneapolis - Model 727-100," Letters to all Boeing 727 Operators, (March 22, 1971), File 6-2000-20-16 and (September 20, 1971), File 6-2000-20-28.

(47) Nanevicz, J. E., and Vance, E. F., "Static Electricity on Flight Vehicles," Proceedings of 1968 Lightning and Static Electricity Conference, Wright Patterson Air Force Base, Ohio, (May 1969), AFAL-TR-68-290, Part II, pp 157-167.

(48) Transport Canada Central Aviation Safety Bulletin C77/01, (1977).

(49) Adams, J. W., National Bureau of Standards, "Summary of NBS Program to Assist USAF in Reducing Flight-Line Fires, Explosions and Personnel Hazards," USAF Static Electricity Symposium, Dayton, Ohio, (September 1977).

(50) Federal Aviation Administration, Washington, D.c., "Report on Conference on Fire Safety Measures for Aircraft Fuel Systems," (December 1967), Defense Documentation Center Reference AD 672036.

(51) Civil Aeronautics Board (USA), "Aircraft Accident Report, Boeing 707, 121 N709 Near Elkton, MD, December 1963, (February 1965), File Number 1-0015.

(52) Short, L. E., "Electrical Bonding of Advanced Airplane Structures," Proceedings of 1968 Lightning and Static Electricity Conference, Wright Patterson Air Force Base, Ohio, (May 1969), AFAL-TR-68-290, Part II, pp 425-441.

(53) Oh, L. L. and Schneider, S. D., "Lightning Strike Performance of Thin Metal Skin," Proceedings of 1975 Lightning and Static Electricity Conference, Culham Laboratory, England (April 1975).

(54) Lockheed-California Co., "Investigations of Mechanisms of Potential Aircraft Fuel Tank Vent Fires and Explosions Caused by Static Electricity," (May 31, 1963), Final Report, Contract No. NaSr-59.

(55) Brenneman, J. J., United Airlines, "A Study of the Fuel Vapor Envelope at Aircraft Tank Vents During Fueling Operations," (December 1963).

(56) Stahmann, J. R. M., "Airflow Velocity Effects on Lightning Ignition of Aircraft Fuel Vent Efflux," Proceedings of 1968 Lightning and Static Electricity Conference, Wright Patterson Air Force Base, Ohio, (May 1969) AFAL-TR-69-290, Part II, pp 239-253.

(57) Newman, F. W., "Surge Tank Protection System," Proceedings of 1968 Lightning and Static Electricity Conference, Wright Patterson Air Force Base, Ohio, (May 1969), AFAL-TR-69-290, Part II, pp 318-323.

(58) Campbell, J. A., National Advisory Committee for Aeronautics, "Appraisal of the Hazards of Friction Spark Ignition of Aircraft Crash Fires," (May 1957), NACA TN 4024.

(59) Inflammabilité des matériaux d'aménagements de cabine d'avion (Centre d'Essais Aéronautique de TOULOUSE) 12-13 October 1971.

(60) Gross, Loftus, Gray, L., "Smoke and Gas Produced by Burning Aircraft Interior Materials," NBS 1968, BSS18

(61) Technical Group Report, AIA CDP 1 - Materials

(62) CNPP - Le feu et la recherche appliquée - Centre national de Prevention et de Protection, Colloque du 19 Avril 1972.

(63) GPCP - Les plastiques et le feu - Journées de Novembre 1976 - Groupement de Promotion pour la connaissance des plastiques

(64) AGARD Aircraft Fire Safety - CP 166, Avril 1975

(65) Thermal Decomposition Products of Aircraft Interior Materials, FAA RD-77-20 (November 1977)

(66) Kourtides, Parker, Gilwee, Lerner, Hilado, Ming, Hsu, "Flammability Characteristics of Aircraft Interior Composites," The Journal of Fire and Flammability, Volume 7, Juillet 1976.

(67) Kourtides, Parker, Gilwee, "Thermochemical Characterization of Aircraft Interior Panel Materials," Center NASA Moffett Field California, Journal of Fire and Flammability, Volume 6, Juillet 1975.

(68) Parker, J. A., Kourtides, D. A., Fish, R., Gilwee, W. J., "Fire Dynamics of Modern Aircraft From a Material Point of View," NASA, Journal of Fire and Flammability, Volume 6, Octobre 1976.

(69) Etude approfondie : La toxicité dans les incendies de cabine d'avions - Ecole Nationale d'Ingénieurs de Constructions Aéronautques - TOULOUSE, MM. BERTRAND - MARCADE, Melle CHABAS, (1976).

(70) Etude de la toxicité des produits de combustion et de pyrolyse de matériaux utilisés dans le bâtiment. MM TRUHAUT - BOUDENE - JOUANY - Archieves des maladies professionnelles de medecine du travail et de Sécurité Sociale, 1975

(71) Conférence de M. JOUANY Symposium de Salt Lake City Mars 1976

(72) Einhorn, "The Nature and Concentration of Combustion Products From Urban Fires," (Université Utah, Salt Lake City), Flammability Research Center, 1973.

(73) Smith, Crane, Sanders, Ewdecott, Abbot, "Material Toxicology Evaluation by Direct Animal Exposure," Symposium Salt Lake City 1976 Mars

(74) Dressler, Skornick, Bloom, Dougherty, "Smoke Toxicity of Common Aircraft Carpete," Aviation Space and Environmental Medecine (1975).

(75) Kourtides, Parker, Hilado, Smouse, "The Effect of Temperature and Air Flow on Relative Toxicity of Polymeric Materials," USF/NASA Toxicity Screening Method, Journal of Combustion Toxicology Aout 1976 - Volume 3.

(76) Hilado, Kourtides, Marcusson, Furst, Parker, "Relative Toxicity of Pyrolysis Products of Some Aircraft Seat Materials," USF/NASA, Journal of Combustion Toxicology - Volume 4 Fevrier 1977.

(77) Hilado, Lopez, M. T., "Studies With de USF/NASA Toxicity Screening Test Method, Effect of Air Flow and Effect of Fabric Dye," Journal of Combustion Toxicology, November 1976, Volume 3.

(78) Hilado, Saxton, Kourtides, Parker, "Relative Toxicity of Pyrolysis Products of Some Cellular Polymers," Journal on Combustion Toxicology - Aout 1976, Volume 3.

(79) Hilado, Slattengren, Furst, Kourtides, Parker, "Relative Toxicity of Pyrolysis Products of Some Synthetic Polymers," NASA/USF, Journal of Combustion Toxicology, Aout 1976, Volume 3.

(80) Annual Conference on Fire Research, PB 273.589, NBS, October 1977.

(81) "Program for Toxicology of Combustion Products," Fire Science Division Center for Fire Research (voir reference 80).

(82) "The Physiological and Toxicological Aspects of Smoke Produced During the Combustion of Polymeric Materials," Contract 7.9005 - NBS, Universite Utah, Salt Lake City, Flammability Research Center (voir reference 80).

(83) The Cleveland Aircraft Fire Tests, 30/6 et 1/7 1966.

(84) The Cleveland Aircraft Fire Test, 24 et 25/7 1966.

(85) Stuckey, Supkis, Price, "Full Scale Aircraft Cabin Flammability Tests," J.S.C. 09060 - NASA TMX 58141, Lyndon Johnston Space Center, Houston TX 77058, Juin 1974.

(86) Stuckey, Brecher, Kuminecz, Supkis, "Full Scale Aircraft Cabin Flammability Tests," J.S.C. 10, 613-NASA TMX 58.172, Avril 1976.

(87) Marcy, J. F., "Air Transport Cabin Mockups Fire Experiments," FAA RD 70-81, NAFEC, Atlantic City, October 1970.

(88) C.E.A.T. P.V. N2 4850 - Partiel N° 3, Essais d'inflammabilité en caisson 1ère campagne d'essais : matériaux elémentaires sans ventilation - Mars 1976.

(89) C.E.A.T. P.V. N6 619800 - Partiel N° 1, Essais d'inflammabilité en caisson 2ème campagne d'essais : matériaux élémentaires essayés avec ventilation. Novembre 1977.

(90) Essais grandeur nature des plastiques techniques, Correlation avec les résultats d'essais à petite Echelle, (Revue Caoutchoucs et Plastiques - Octobre 1977) Nelson -Bridgman - O. Connell - Williams.

(91) Kourtides, Parker, Hilado, Anderson, Tustin, Arnold, Boeing, Gaume, Binding, Miksla, Douglas, "Fire Safety Evaluation of Aircraft Lavatory and Cargo Compartments," Journal Fire Flammability - Janvier 1976 - Volume 7.

(92) Hilado, Smouse, Leon, "A Large Hemispherical Chamber for Fire Toxicity Tests," NASA USF, Journal of Combustion Toxicology - Volume 3, Aout 1976.

(93) Hilado, Cumming, Kourtides, Parker, "Systems for Animal Exposure in Full Scale Fire Tests," NASA/USF, Journal of Combustion Toxicology - Volume 4, Mai 1977.

(94) P.V. N6 766600 - Partiel 1 - C.E.A.T., Description de l'installation de'essais destinée à l'étude toxicologique des gaz et fumées de combustion - Mars 1978.

(95) "Evaluation of Toxicity of Combustion Products," Johns Hopkins University, NBS G.T. 9019, Annau et Coll (voir reference 80).

(96) Kubaschewski, O., and Hopkins, B. E., Oxidation of Metals and Alloys, 2nd Ed., Buttersworths, London (1962).

(97) Kubaschewski, Evans, and Alcock, Metallurgical Thermochemistry, 4th Ed., Pergamon Press (1967).

(98) Fontana, M. G., and Greene, N. D., Corrosion Engineering, McGraw-Hill (1967).

(99) Reynolds, W. C., "Investigation of Ignition Temperatures of Solid Metals," NASA TND-182 (October 1959).

(100) Gaydon, A. G., and Wolfhard, H. G., Flames, Chapman and Hall Ltd., London 2nd Ed., (1960).

(101) Brzustowski, T. A., and Glassman, I., "Vapor-Phase Diffusion Flames in the Combustion of Magnesium and Aluminum: I Analytical Developments," published in Heterogeneous Combustion, Progress in Astronautics and Aeronautics 15, AIAA, Academic Press, New York, (1964).

(102) Brzustowski, T. A. and Glassman I., "Vapor-Phase Diffusion Flames in the Combustion of Magnesium and Aluminum: II Experimental Observations in Oxygen Atmospheres Balance," Published in Heterogeneous Combustion, Progress in Astronautics and Aeronautics 15, AIAA, Academic Press, New York (1964).

(103) Mellor, A. and Glassman, I., "Vapor-Phase Diffusion Flames in the Combustion of Magnesium and Aluminum: III Experimental Observations in Carbon Dioxide Atmospheres," Published in Heterogeneous Combustion, Progress in Astronautics and Aeronautics 15, AIAA, Academic Press, New York (1964).

(104) Wolfhard and Parker.

(105) Harrison, P. L., "The Combustion of Titanium and Zirconium," Seventh Symposium (International) on Combustion, London and Oxford, August 28-September 3, 1958, London, Butterworths Scientific Publications (1959).

(106) Hilado, C. J., Flammability Test Methods Handbook, Technomic Publishing Co., Inc., Westport CT (1973).

(107) Glassman, I., and Hansel, J. G., "Some Thoughts and Experiments on Liquid Fuel Spreading, Steady Burning and Ignitability in Quiescent Atmospheres," Fire Research Abstracts and Reviews 10, 217-234 (1968).

(108) Roberts, A. F., "Spread of Flame on a Liquid Surface," Ph.D. Thesis, Imperial College, London 1959.

(109) National Materials Advisory Board, "Aircraft: Civil and Military," Report of the Committee on Fire Safety Aspects of Polymeric Materials, Publication NMAB 318-6, National Academy of Sciences, Washington D.C., 1976.

(110) Kuchta, J. M., "Fire and Explosion Manual for Aircraft Accident Investigators," Bureau of Mines Report No. 4193, Air Force Aero Propulsion Laboratory, Wright Patterson Air Force Base, Ohio, Technical Report AFAPL-TR-73-74 (August 1973).

(111) Sarkos, C. P., "Titanium Fuselage Environmental Conditions in Post-Crash Fires," Federal Aviation Administration Report No. FAA-RD-71-3 (March 1971) pp 49.

(112) Geyer, G. B., "Evaluation of Aircraft Ground Fire Fighting Agents and Techniques," Federal Aviation Administration Report No. FAA-RD-71-57, (February 1972), pp 188.

(113) Graves, K. W., "Fire Fighter's Exposure Study," Wright Patterson Air Force Base Technical Report AD-722744/AGFSRS-71-2, December 1970.

(114) Neill, D. T., Welker, J. R., and Sliepcevich, C. M., "Direct Contact Heat Transfer from Buoyant Diffusion Flames," J. Fire and Flammability 1, 289 (1970).

(115) Russell, L. H., and Canfield, J. A., "Experimental Measurements of Heat Transfer to a Cylinder Immersed in a Large Aviation Fuel Fire," To be published.

(116) Gordon, W., and McMillan, R., "Temperature Distribution Within Aircraft Fuel Fires," Fire Technology 1, 52 (1965).

(117) Zabetakis, M. G., "Flammability Characteristics of Combustible Gases and Vapors," Bureau of Mines Bulletin 627, 1965, pp 121.

(118) Burgess, D. and Zabetakis, M. G., "Fire and Explosion Hazards Associated with Liquified Natural Gas," Bureau of Mines Report RI 6099 (1962) pp 33.

(119) Cahill, J., "Flame Intensity Investigation - Report No. 7, Measurement of the Intensity of Various Flames," Rolls-Royce Ltd., Aero Engine Division IFR 900008, (May 1967).

(120) Beardsley, G., "Flame Intensity Investigation - Report No. 9, Measurement of the Intensity of Flames Produced by Atomised Flammable Fluids," Rolls-Royce Ltd., Aero Engine Division IAR 08037 (January 1969).

(121) Fu, T. T., "Heat Radiation From Fires of Aviation Fuels," Paper Presented at the 1972 Fall Meeting, Eastern States Section of the Combustion Institute, Princeton University, Princeton, New Jersey (December 1972).

(122) Wilford, S. P., "RAE Safety Fuel Newsletter," LSP/191/034 Materials Department, Royal Aircraft Establishment, Farnborough, Hants, (November 1, 1974).

(123) Wilford, S. P., "RAE Safety Fuel Newsletter No. 2," LSP/191/034/SPW Materials Department, Royal Aircraft Establishment, Farnborough, Hants (December 2, 1975).

(124) Wilford, S. P., "RAE Safety Fuel Newsletter No. 3," LSP/191/034/SPW Materials Department, Royal Aircraft Establishment, Farnborough, Hants (July 20, 1977).

(125) Weatherford, W. D. Jr., and Wright, B. R., "Status of Research on Anti-mist Aircraft Turbine Engine Fuels in the United States," AGARD/NATO 45th Meeting, Propulsion and Energetics Panel, "Aircraft Fire Safety," Rome, Italy, Paper No. 2, (April 7-11, 1975).

(126) Weatherford, W. D. Jr., Personal Communication (1978).

(127) Eklund, T., "Experimental Scaling of Modified Fuel Breakup," FAA Report No. FAA-RD-77-114 (August 1977).

(128) Mannheimeir, R. J., "Rheology of Antimist Fuels," FAA Report No. FAA-RD-77-10 (January 1977).

(129) Miller, R. E., and Wilford, S. P., "Simulated Crash Fire Tests as a Means of Rationing Aircraft Safety Fuels," RAE TR 71130.

(130) Ahlers, R. H., "Full-Scale Aircraft Crash Tests of Modified Jet Fuel," Report No. FAA-RD-77-13.

(131) Russell, R. A. Jr., "Small-Soale Impact Tests on Crash Resistant Fuels," FAA-RD-71-49.

(132) Wright, B. R., Stavinoha, L. L. and Weatherford, W. D. Jr., "A Technique for Evaluating Fuel Mist Flammability," USACCL Technical Report Prepared by USAFLRL, AD 776965 (December 1973).

(133) Miller, R. E., "Fire Test Methods for Antimisting Kerosene (AMK)," Materials, Department, Royal Aircraft Establishment, Farnborough, Hants.

(134) Coordinating Research Council, Inc., "Aviation Fuel Safety - 1975," Prepared by Aviation Fire Safety Report Task Force, Coordinating Research Council, Inc., New York New York, November 1975.

(135) MacKinven, R., Hansel, J. G., and Glassman, I., "Influence of Laboratory Parameters on Flame Spread Across Liquid Fuels," Combustion Science and Technology 1, 293-306 (1970).

4. FIRE PROTECTION ENGINEERING ASPECTS OF AIRCRAFT FIRE SAFETY - SUBGROUP III

4.1 Background

At the beginning of this search to find new and improved ways to deal with the potential fire threats to transport aircraft, it was recognized that a jet powered aircraft comprises a number of necessary elements such as fuel, electrical and related structural (lightweight) and combustion system components which are all potentially hazardous unless controlled. When managed properly these systems are supportive elements for a normally operating aircraft, capable of the normal operations of take-off, landing, sustained flight, taxiing and mooring. As discussed in Section 2 these operational phases can, under accidental circumstances, give rise to an aircraft which operates abnormally in these regimes and can give rise to the scenario types referred to as post-crash, inflight, and ramp fires. Depending upon the accident scenario, so defined, interactions may occur among the identified hazardous elements, such as ignition sources, fuels, interior systems, aircraft structure, passenger related components such as bring aboard and stored baggage, galley supplies, etc. The initiation of a significant fire chain through the aircraft system, requires a certain minimum size ignition source (heating rate and duration) and flame or radiant contact with combustibles to effect initiation after which time must pass to allow the fire to grow to a size capable of modifying, changing, or destroying key aircraft operating systems required for normal aircraft operation. For purposes of this study, three interdependent aircraft systems have been identified as the key matrix elements required for survivability, namely, structure, propulsion and fuel, and the habitable cabin environment.

Information has been collected, reviewed and correlated for this section which related to the effects of the fire growth through these three systems on survivability. This approach has provided a rational method for examining the impact of probable aircraft fire scenario, fire threat, and the resulting system response to provide useful recommendations for systems improvement (fire hardening) and operational consideration to reduce the level of the fire threats. This approach has been used to develop an understanding of the interaction of the identified aircraft systems with the thermal environment to estimate the critical failure levels, and then to provide interdictive techniques to suppress the fire threat by limiting available fuel, minimizing ignition sources, reducing air flow, or changing configurations. In those cases where it is feasible to fire harden the systems, per se, providing more fire resistant materials

and fire protection have been considered. Support for this fire engineering approach has structured the activities of two other committees, namely the fire threat from possible scenarios and the combustion response of the systems, respectively. The interaction of the product of these two groups has in fact provided qualitative guidance especially to the structures and fuels contribution of fire engineering. To be sure analytical risk assessment models for systems fire threat have been sought for during this study.

Such models are extremely rare and usually highly inaccurate. During the course of the Subgroup III activity one valuable analytical survival model has been developed which may be useful for passenger survivability inflight and in some limited post-crash fire scenarios. Such a model as this one which predicts passenger lethality from toxic gases and/or heat as a function of fire size (growth) can easily prioritize the threat as well as help make decisions as to where the most beneficial modifications can be made. For example, it may be concluded from this model that the dominant fire threat to human passengers in small to moderately sized inflight fire of state-of-the-art materials is from toxicant gases rather than thermal effects.

A second source of information has been employed by the fire engineering group to effect improvements. Subgroup I has attempted direct analysis of accident scenarios as available. The main criticism and weakness of the generalized scenario approach to providng useful leads to applied fire protection engineering is that they are always too general to be very useful in effecting improved survivability. This results because of the unavoidable lack of time dependent fire data (aircraft are rather completely destroyed). Very useful data could be obtained for the development of scenarios from detailed incident reports. Unfortunately these are not as complete as formal accident reports. Simulation of accident scenarios by full-scale testing still remains the best source of fault analysis data for scenario development. Unfortunately tests of these kind are at present very limited. The extent of fire severity in most aircraft accidents often makes it impossible to determine deductively the progress of the fire impact from initiation to termination, that is, the regime in which applied fire engineering can make the most effective enhancement of survivability. Scenarios, however synthetic and general, can with qualifications be used to classify fire dominant accidents as inflight, post-crash and ramp types. For purpose of this report and this section, the committee has accepted these three categories of aircraft fire and their delineations as guidelines for fire threat, fire hardness and failure mode definitions for testing, materials selection, and finally application of fire protecting engineering concepts. One can assure some development among these three categories. Interior fire may borrow features from all three kinds of scenarios, for example, the fuel fire by the door of a moored aircraft. To be sure this classification can yield some redundancy in fire engineering analysis but does in some cases identify the most probable threat source, elimination of which can derive the greatest benefit.

With respect to the activities of the fire safety engineering group, it should be pointed out that a definite technical road map has been followed for structuring the contents of the individual summaries, conclusions, recommendations and abstracts dealing with the potential remedial opportunities to put down the aircraft fire. This road map has essentially involved tracing the fire chain as it proceeds through the aircraft, substantially effecting propulsion and structural systems. A technical summary, beginning with the flammability of the fuels system, per se, the transition to a Jet A type fuel, seems most important. A second priority is possible once this transition has occurred, namely the use of antimisting agents to reduce the probability of ignition of spilled fuel. Since post-crash fires, the dominant fires in aircraft, strengthening the particular wing sections of locational fuel tanks to prevent fuel spillage becomes another important option. Techniques for rerouting fuel lines and hardening of fuel tanks is related. Moving from these first lines of defense to the fact that a fire will occur under certain circumstances, improvements in the fire hardness of current aircraft evacuation slides may provide enhanced survivability. Hardening of fuselage and windows with new high char yield transparent composite materials can be expected to reduce the penetration of the fire threat in terms of the short term fire impacts of flashover and toxic gas debilitation.

It is in the area of the ramp fire and the inflight fire that the possibility of improved detection systems and improved suppression agents to deal with the fire become important. This is not only true in the case of the unoccupied void space in the aircraft, such as lavatories, galleys and cargo base, but also applies to potential improvements that may be made with new combinations of detectors and new effective solid quenching agents to deal with the nacelle fire.

It has become clear from both the examination of the analytical model dealing with the effects of toxic gases and heat on passengers that the utilization of a toxic fume hood or modification of existing oxygen systems stands out as foremost recommendations to provide passenger protection. With respect to materials of construction for aircraft involved in fire scenarios, one can expect a gradual improvement over the next five to ten years as new fire resistant structural and decorative materials are gradually introduced into modern transport aircraft as permitted by availability and cost. The information to support this general technical summary is given in the following sections. More detailed recommendations are given as the final concluding section.

4.2 Propulsion and Fuel Systems

4.2.1 Background

Aircraft propulsion and fuel systems possess a diversity of potential fire and explosion hazards. Although the principal threat is associated with the hydrocarbon fuel, attention must also be given to other sources of fire such as hydraulic fluids, lubricating oils, structural materials, and electrical equipment. In addition to the variety of potential combustibles, a number of fire ignition sources are also possible such as hot surfaces, friction sparks, electrical arcs and sparks, hot gases and, particularly to military aircraft gunfire. The achievement of an effective fire protection capability for aircraft entails the critical assessment of the probability of a combustible and an ignition source coming together; the damage potential associated with such an event; the application of preventative measures in the design of the aircraft to minimize such an occurrence; and the incorporation of appropriate fire surveillance and fire and explosion suppression techniques to counteract the remaining "high risk" fire problems. The subsequent discussion will be directed towards the identification of typical propulsion and fuel system fire scenarios; the effectivity of state-of-the-art fire protection technology in coping with these typical fire situations; and the identification of impending developments which if successful and applied could improve fire protection capability.

4.2.2 Propulsion Installations

4.2.2.1 Fire Scenarios

Propulsion installations and other power generation equipment such as auxiliary power units which are utilized on civilian and/or military aircraft have always been recognized as inherently providing a high fire threat potential. The fire threat exists because of the location of various flammable and combustible fluids proximate to various sources of ignition, e.g. hot engine surfaces. Accordingly, it is not surprising that considerable fire protection engineering attention is provided to the safe integration of power generation equipment on-board aircraft. The fire protection approach generally embodies fire prevention, fire containment and isolation, and detection and extinguishing capabilities as necessary. In view of the extensive aircraft accident/incident experience with the above equipment as well as the considerable engineering fire test experience with engine installations, delineation of typical fire scenarios should be possible at least on a qualitative basis. The scenarios, if properly characterized, should enable prediction of fire initiation, propagation, and severity for various materials as influenced by flight environment factors and in-turn enable characterization of the survivability enhancement/benefits provided by various fire protection measures. In attempting the above objective, consideration must be given to: (1) fire dynamics under representative engine operating environment and configuration conditions, (2) the interaction of "unwanted" fires with typical aircraft structure materials in terms of damage potential, (3) effectiveness of various active and passive measures available to cope with or counteract the fire threat and (4) delineation of technology opportunities to significantly enhance fire survivaiblity. The effectivity of protection techniques must be assessed in terms of weight penalty and life cycle cost considerations where possible.

The preponderance of operational military and civilian aircraft are powered by turbofan engines and the outlook for at least the next 25 years indicates that the turbofan will continue to be the "workhorse" engine. Accordingly, the turbofan engine installation has been selected for the delineation of the typical propulsion system fire hazard scenarios.

Modern day civil and military aircraft exhibit a wide variance in engine/airframe integration configurations. These include wing-pod mounted (747, 707 and B-52), fuselage-pod mounted (DC-9), internal fuselage (F-111), and the combinations of internal fuselage and pod mounted (727) configurations. Major engineering attention is given to propulsion areas where it is necessary to: (1) surround the fire zones with fire proof materials so as to confine a fire and prevent its penetration into adjacent unprotected aircraft compartments, (2) to provide for rapid detection of a fire, (3) to allow for shutting off the flow of flammable fluids and (4) to extinguish the fire. Limitations of such protection, shown by the accident experience, are that no effective control of fire can be assured if the boundaries of the fire zones are breached or if the crew fails to activate shutoffs promptly. Compromise of fire zone boundaries for example have occurred due to internal engine failure (fan blade separation, compressor and turbine stage failures) resulting in penetration of the engine case and adjacent fire wall of airframe structure. Proximate location of fuel tanks to the failed engine - projectile pattern aggravates the resulting fire severity by violation of the fire zone boundary, generation of an uncontrollable fuel leakage situation, and the possible direct or secondary initiation of internal fuel tank fire and/or explosion. Particular engineering design considerations must be pursued to reduce fuel tank vulnerable area in the event of catastrophic engine failure. Based on typical operational aircraft engine/ airframe integration configurations, it is evident that the propulsion fire scenarios must not only provide attention to the fire threat external of the engine but within the

designated fire zone area and also to the engine internal failure induced fire situation. The latter must include as separate possible fire scenarios consideration of engine response due to fuel ingestion, internal oil leakage, as well as the combustion/fire characteristics of internal engine components (fan and compressor blades etc.) under dynamic frictional loading conditions.

The propulsion installation failure mode and effects analysis results in the postulation of numerous potential fire scenarios. Five representative fire scenarios were developed and previously discussed in Section 2.2.5 of this report.

4.2.2.2 Fire Protection Engineering

On the basis of the aircraft mishap analysis performed by Subgroup I, the propulsion installation fire scenarios have not been major contributors in recent fire related fatal aircraft accidents. This experience indicated that current fire protection engineering criteria and measures, particularly for the intact engine and nacelle scenario, are adequate. Although improvement in fire detection reliability, particularly from the viewpoint of reducing false warning problems, is desirable, relative priority of such activity compared to other aircraft safety areas is not high. In reviewing propulsion installation problems, it is quite apparent that continued strong attention must be provided to the potential vulnerability of aircraft to fires induced by uncontained engine failures and the internal engine metal fire.

4.2.2.2.1 Frequency of Uncontained Engine Failure

Details of uncontained engine failures experienced by commercial transport aircraft, extracted from Reference 4.7.1 are listed in the following tables.

Table 4.1 - Uncontained Engine Failure Experience

Damage Category	No. of Occurrences			Failure Rate Per Million Engine Hours	Fire Hazard Potential to Aircraft
	Discs and Spacers	Blades	Total		
Nacelle	47	48	95	0.23	None
Minor Airframe	71	60	131	0.31	Controlled
Significant Airframe	34	10	44	0.11	Uncontrolled
Severe Airframe	4	1	5	0.01	Catastrophic
Total	156	119	275	0.66	

There were 49 instances corresponding to a frequency of 0.12 per million engine hours (or once in 2 million aircraft hours for a four engine aircraft) where there was the possibility of fire spreading in an uncontrolled manner. The basic causes for these failures are delineated in Table 4.2.

Table 4.2 - Engine Failure/Potential Uncontrolled Fire Spread

Failure Cause	No. of Failures	% of Total	% of Known Causes
Design	18	37	42
Manufacture	11	23	26
Control and Operational	6	12	14
Maintenance	4	8	9
Others	4	8	9
Unknown	6	12	--
Total	49	100	100

It appears that there is still potential for improvements in design and manufacture and that these could reduce the rate to some 30 to 40% of its current value.

4.2.2.2.2 The Significance of Engine Fires

References 4.7.2 and 4.7.3 have been used to analyze the importance of engines as sources of aircraft fires. Reference 4.7.2 contains some 113 turbine transport aircraft fire accidents grouped as follows:

Table 4.3 - Engine Failure/Total Accidents

Occurrence	All Occupants Killed	Some Occupants Killed	Some Serious Injuries	Minor or No Injuries	Total
Inflight	0/8	0	0/1	12/16	12/25
Post Impact	1/20	0/21	2/11	2/14	5/66
On Ground	0	0	7/13	6/9	13/22
Total	1/28	0/21	9/25	20/39	30/113

Notes: 1. All inflight engine cases involve engine fires or disintegration.

2. All post impact engine cases involve engine failures followed by aircraft handling problems.

3. One ground engine case involved an engine failure during take-off, the remaining 12 involved engine fires.

Table 4.4 - Engine Fire or Disintegration/Total Accidents

Occurrence	All Killed	Some Killed	Some Serious Injuries	Minor or No Injuries	Total
Inflight	0	--	0	0.75	0.48
Post Impact	0	0	0	0	0
On Ground	--	--	0.54	0.56	0.55
Total	0	0	0.36	0.49	0.26

This implies that the NTSB study found engine breakup responsible for no fatalities, serious injuries only on ground accidents and, otherwise, no worse than minor injuries. Half of the inflight and ground accidents were due to this cause.

Consideration of accidents listed in reference 4.7.3 shows that, of the 85 inflight fire accidents, 57 - or 67% - involved engines and 11 of these included another cause; 8 of these 11 were combined with fuel fires and 4 of these resulted in fatal accidents compared with 2 of the 46 where engine fires alone occurred. The one case of a combined airframe fire was also fatal. Full details are shown in the following table:

TABLE 4.5 - Engine Inflight Fires/Other Subsystem Accidents

Type of Fire	Engine	Engine & Fuel System	Engine & Cabin	Engine & Airframe	Total
No. of Accidents	46	8	2	1	57
No. of Fatal Accidents	2	4	0	1	7
No. on Board	2793	618	103	21	3535
No. on Board Fatal Accidents	19	262	0	21	302
No. of Deaths	15	140	0	1	156
Proportion Killed of Total on Board	0.005	0.0227	0	0.048	0.044
Proportion Killed in Catastrophic Accidents	0.789	0.534	0	0.048	0.517

This underlines the dominance of the combined engine and fuel system fires which result in 8 of 9 deaths with only 4 of the 7 fatal accidents; furthermore 1 in 2 of these accidents is fatal. When an engine fire occurs alone the chance of being killed is 0.5%; when it is combined with a fuel system fire this increases 45 fold to 22.7%.

4.2.2.2.3 The Combined Engine and Fuel Fire

As is apparent, design is normally satisfactory in preventing engine fire from spreading to the airframe and particularly to the fuel system. Only when the engine failure is disruptive, resulting in break-up of components and penetration of the external casing, with consequent damage to fluid and electrical systems, is a hazardous situation likely to eventuate. The reason for a disruptive failure is either due to an inability to survive the entry of foreign bodies, a failure of the control system leading to over-stressing from an overspeed condition or weaknesses in maintenance, manufacturing or design.

The ability to ingest foreign bodies, principally birds, rain and hail, is the subject of agreed design criteria; at least for transport aircraft bird strikes occur nearly always close to airports so that, provided the deterioration in aircraft state following such a strike is not too rapid, a safe landing and evacuation can be carried out. Hail and rain ingestion are likely at lower altitudes whilst the aircraft is still near an airport; however, a landing may not be possible for some tens of minutes, as opposed to some minutes for a bird strike.

Overspeeding of rotors is also covered by agreed design criteria so it is mainly defects of maintenance, manufacturing or design which appear likely to lead to engine break-up.

Appendix D (reproached from reference 4.7.4) sets down the appropriate design requirements with acceptable means of compliance for proving the satisfactory integrity of equipment with high energy rotors.

Appendix D, Section 1, relating to engines, is part of J. A. R. - E., while Section 2, referring to the protection needed on airframes if engines cannot contain their debris, is currently under discussion for incorporation into J. A. R. - 25 (Joint Airworthiness Regulations (J. A. R.)) are agreed by the Civil Airworthiness Authorities of Belgium, France, Federal Government of Germany, Italy, the Netherlands, Sweden and the UK. Such requirements should provide adequate assurance of safety.

Persistent fires can arise from the use of titanium in engines and result in considerable difficulty or impossibility in rapid extinguishment. Appendix E (from reference 4.7.4) outlines methods of avoiding the problem which, if it arises, can eventually result in the fire spreading to the remainder of the aircraft.

With respect to the propulsion contribution to the aircraft survivable impact fire scenario, as mentioned earlier, engines can serve both as an ignition source and a source of combustible fluid leakage due to the breaking of fuel lines during the disruptive deceleration phase. Consequently, design and

installation measures to limit fluid leakage, for example, by incorporation of isolation valves and proper routing of fuel lines in a manner which is complementary to the entire fuel tank - fuel transfer system performance and fuel containment goals should be pursued.

4.2.3 Fuel System

The fuel system represents a major portion of the aircraft which is vulnerable to fire and explosion. Consequently, it should not be surprising that the fuel system and the large quantity of flammable fluid contained therein can and often is involved in a variety of fire scenarios many of which result in catastrophic property damage and loss of lives. Fuel system fire involvement can occur under ramp, aborted take-off, inflight and crash conditions.

4.2.3.1 Ramp Fires

The principal fire scenario for the fuel system under the ramp or parked aircraft mode is associated with static electricity generation within the fuel tanks during fuel servicing operations.

Aviation fuels inherently pose a fire and explosion threat, however, the risk can and has been minimized through the application of engineering preventive measures and proper handling procedures. At the present time there are three hydrocarbon jet fuels in use for military and/or civil aviation applications. These fuels are designated as JP-4 (Jet B), Jet A-1 (JP-8) and JP-5 and vary principally in volatility. Each of these fuels under sea level, closed environment, equilibrium mixing conditions exhibit a flammability temperature range (lean and rich limits) in air which is related to their respective volatility. Under the above type conditions, JP-4 fuel exhibits a flammability range from approximately -10°F to +60°F, JP-8 from approximately +105°F to 185°F, and JP-5 from approximately +140°F to 220°F. For all practical considerations, flammability vapor-air mixtures of any of those fuels exhibit essentially similar ignition and flame propagation characteristics. The relative safety of one fuel versus another consequently for closed systems is related to the probability or frequency with which flammable vapor-air mixtures are likely to be present within the system under the typical environmental (temperature, pressure) conditions of use. In the case of any of these fuels, it should be pointed out that the conditions of fuel introduction can result in mist/spray-air mixtures capable of extending the combustible range to lower temperatures. It should become very apparent that in the case of JP-4 under world-wide conditions of use, existence of flammable vapor-air mixtures in fuel servicing trucks, and aircraft is a very frequent occurrence. In the case of JP-8 and JP-5 the existence of vapor-air mixture threat is markedly less and the principal threats relate to heterogeneous (mist/spray) mixtures. The existence of a flammable/combustible fuel-air mixture in itself is not damaging unless an ignition is introduced to trigger the combustion process. Various ignition sources can be postulated, but in the fuel handling process the one of major concern is electrical spark discharge either from equipment or electrostatically induced. With respect to susceptibility to electrical spark ignition, once again the flammable vapor-air mixtures exhibit the greatest vulnerability requiring the lowest ignition energy levels. It should become apparent, in view of the above brief discussion, that the more volatile JP-4 fuel poses the greatest susceptibility to destructive combustion initiation, and therefore, hazard prevention measures based on JP-4 as the threat, automatically result in a greater safety margin when either JP-8 or JP-5 is utilized.

Available world-wide accident/incident data for the period March 1966 to present was analyzed by the U.S. Air Force in order to assess the frequency of occurrence and the effectiveness of current engineering and operational practices to minimize the aircraft static electricity hazard during the fueling. The bulk of the occurrences for which information was available involved U.S. Military experience. In addition, many accidents/incidents involved aircraft fueling vehicles. These mishaps have involved servicing of JP-4 in JP-4, low volatility fuel into JP-4, low volatility fuel into low volatility fuel, JP-4 into previously unwetted polyurethane foam, JP-4 into previously wetted JP-4 polyurethane foam, and low volatility fuel into previously wetted JP-4 polyurethane foam. Although no incident involving servicing of JP-4 into low volatility fuel or JP-4 into previously low volatility fuel wetted polyurethane foam have been identified, for all practical purposes there are no reasons why such activities should not also be vulnerable to the static electricity induced theat.

The generation of static electricity during the movement or transfer of nonconducting fluids such as hydrocarbon jet fuels many years ago resulted in the explosion of several aircraft and refueling vehicles. Similar mishaps occurred on the industrial side also. Extensive investigations were conducted, most notably by Shell Research, the Coordinating Research Council of the American Petroleum Institue, Exxon Company and Mobil Company. These investigations have provided a good understanding of the charge generation and relaxation factors involved the transfer of jet fuels and their interaction with the hardware components in the system. In other words, minimization/prevention of the static electricity induced fuel tank explosion hazard must provide attention to all elements in the fuel distribution loop from the source to the fuel tank accepter vessel on-board the aircraft. Components, fuel flow rates, etc., must be

judiciously engineered/selected to preclude fuel charge generation and where charge generation does occur to allow for its safe controlled dissipation to earth. The application of the above approach to the aircraft fueling operation and internal fuel tank design has resulted in an extremely outstanding safety record with regard to the static electricity threat particularly in consideration of the millions of fuelings that have taken place around the world during for example the past ten years. It should be noted that in many parts of the world an antistatic additive is utilized in the fuel to increase its conductive properties and thereby significantly improve charge dissipation during the loading process. The use of such an additive in Canada for the past 13 years has negated the hazard, whereas previously, mishaps occurred annually.

In the case of the baffle foam filled tanks, recent studies in the United States and United Kingdom which are still in progress indicate that fuel impingement on these porous materials cause localized electrical charge generation which can result in incendive discharge capable of igniting fuel vapor-air mixtures. Combustion manifests itself in a short-term, flash fire effect resulting in scorching of the foam and possible heat damage to the fuel cell material. The explosion protection afforded by these materials inherently prevents any catastrophic effects. It appears that this low risk hazard with integral foam materials can be essentially neutralized by modification of fuel inlet design criteria and or use of antistatic additives in the fuel.

A special concern is often voiced with respect to "switch loading" of fuels which is a term commonly used to mean the introduction of a low volatility fuel into a tank containing remnants of higher volatility fuel such as JP-4. As indicated earlier, several mishaps involving "switch loading" have occurred, all of these as best can be determined, were attributable to inherently hazardous fill procedures or the presence of a now recognized charge generation situation in the system and not associated with the switch loading process per se. Switch loading in essence results in the blending of a low volatility fuel with a higher volatility fuel resulting, depending on the ratio of the two, in a final fuel mix having intermediate volatility characteristics. The end result is the modification of the flammability range somewhere between those exhibited by the neat fuels themselves. Consequently, flammable vapor air mixtures can exist under equilibrium conditions in a different environmental temperature range and one that is more closely aligned with operational conditions.

But this situation is no different than that experienced with straight JP-4 fueling operations. The blended fuel vapor air mixtures do not exhibit an electrical spark ignition susceptibility any different than JP-4 and in addition the blending of the fuels does not pose any unique static electricity charge generation condition. Consequently, the threat is no different than that posed by JP-4 itself; and handling procedures, servicing rates, and system safety design criteria established for JP-4 are equally applicable to the "switch loading" operations.

In summary, all fuels pose a fire threat which can be minimized by proper equipment design and handling procedures. In general, the more volatile fuels such as JP-4 drive the safety requirements. Switch loading, per se, does not pose any hazards which are not already manifested in the more volatile fuel such as JP-4. Consequently, loading rates, handling procedures, etc., deemed safe for JP-4 fueling operations are directly applicable to switch loading operations. In those instances where fueling operations are conducted with passengers on board the aircraft particularly where Jet B or switch loading is being utilized, special precautions such as reducing fuel loading rates should be implemented. The element of risk could be also improved if one were to implement additional active or passive protection measures such as inerting of all fuel tanks. In the majority of mishaps, however, the occurrence can be attributed to mal-design practice, unknowingly introducing a charge generator condition within the system, the following of a previously identified hazardous fill procedure, or the occasional presence of a fuel batch that for some reason exhibits a high charging tendency. Hindsight indicates that many of the aforementioned mishaps are now preventable by appreciation of lessons learned.

4.2.3.2 Inflight

Somewhat similar to the aforementioned ramp operational mode, aircraft fuel systems are also vulnerable to inflight fire and explosion. The ignition threats, however, are not principally static electricity related, but rather include threats such as lightning strikes, electrical equipment failure, heating due to external fires such as fires in adjacent propulsion installations, and penetration by metal fragments emanating from engine failure. Fuel tank explosion inflight must always be considered a serious hazard because of the catastrophic effects to passengers and aircraft. Although the frequency of inflight fuel system explosions has fortunately been very low, the potential catastrophic effects have been substantiated. Based on this Working Group's analysis of accident data, the catastrophic occurrences have involved Jet B (JP-4) fuel or mixtures of Jet B, and Jet A type fuels. These provide a greater likelihood of flammable vapor-air mixtures being present in the tank under subsonic flight operations. The experience also implies an inherent safety advantage for a Jet A type, low volatility fuel in this fire scenario. In addition, the mishap experience more importantly reflects the effectiveness of established lightning protection and

electrical system design requirements which are utilized on operational aircraft. Obviously more or continuing research is needed, but the benefits or prior engineering hazard prevention measures are clearly evident.

Several active and passive approaches for inerting and suppressing the explosion hazard associated with aircraft fuel tanks are available or under development. Some of these currently find application for military aircraft systems. Since these may provide multiple benefits to ramp, inflight and crash scenarios, their detailed discussion will be included in the crash survivability section which follows.

4.2.3.3 Crash

Accident experience indicates that the most frequent transport aircraft post-crash fire scenaric involved wing separation, release of large quantity of fuel, with a resultant rapidly propagating and intense external fire. Human survival is dependent upon rapid egress which amounts to a race against toxic product, smoke and heat effects initially primarily associated with the external fuel fire. Another important scenario involves ignition of fuel from damaged or punctured fuel tanks and severed fuel lines.

4.2.3.3.1 Crash Resistant Fuel Systems

The ideal way to negate these scenarios would be simply to eliminate fuel spillage. The U.S. Army used this approach and successfully eliminated post-crash thermal fatalities from the helicopter fleet. In retrospect there seems to be four major factors which provided the basis for success of the program.

a. The simple decision was made that the loss of life in helicopter post-crash fires was inexcusable and could not be tolerated. As a result, a no-holds-barred effort was initiated and backed by the highest authorities in the U.S. Army. The positive attitude and approach generated fertile ground for accomplishment of the assigned task.

b. The approach made maximum use of full-scale crash tests to provide the most accurate assessment of problem areas and evaluation of those "fixes" which seemed worthy. Rather than be satisfied with simulation or mockup demonstration, actual crash testing was the only acceptable certification of a candidate improvement or design criteria. In many cases when certain design criteria were questioned as being too severe or restrictive, the crash data could be cited as unqualified justification.

c. The crashworthy fuel system (CWFS) is based entirely on fuel containment during and after the impact event. On the surface, this factor may seem insignificant but a closer look at its advantages will show its importance. The concept will work regardless of fuel type - Jet A, Jet B, antimisting fuel, or thickened fuel. Should the Army change fuel or use multiple fuels it will not effect the CWFS. It is independent of the fuel level or ullage content at impact. It is entirely passive and requires no action by the pilot nor is it dependent upon some other subsystem for activation. Because no fuel spillage results during the impact there is no requirement to minimize ignition sources during the crash, activate an extinguishing system, CFR, or rapid crew egress. These factors are especially important during crashes in a tactical environment or wilderness location.

d. All aspects of crashworthiness were integrated in the development phase to maximize occupant survival. Human survival envelop, crash kinematics, airframe crashworthiness, restraint systems, occupant environment, and post-crash fire prevention were addressed together to insure that the airframe provide maximum potential for occupant survival and that the CWFS functioned in the most severe survivable crash (reference 4.7.5). It also insured that all aspects of survivability were addressed and that fairly simple but potentially lethal shortcomings were not overlooked.

The highly visible success of the CWFS makes direct application of this technology to the transport fire problem tempting. However, the obvious differences in aircraft characteristics and crash scenario may dictate another course of action. Let us examine the important design characteristics of the CWFS and attempt to identify the potential for its application on the large transport.

The heart of the CWFS is the crashworthy tank. It is the result of a material development program where the crash environment was analyzed and specifications identified which were necessary for a material to contain fuel during the crash event. The material had to tolerate large strains and be resistant to tearing and cutting from damaged structure and foreign objects. The test criteria specified in MIL-T-27422B are used to select tank materials to survive the helicopter crash environment. These tests include measurements of tear and puncture resistance, environmental stability and long term leakage. Most materials developed to date which satisfy this specification are nylon fabric/rubber laminates which also contain specialized sealing provision for combat threats. It is equally important that the basic tank

material be fabricated into a complete tank which is crash resistant. This fabrication normally involves cut and try lay-up which may vary in thickness on ply orientation as dictated bv tank geometry and potential crash loads. In addition, all fitting attachments to the tank must be strong enough to withstand crash loads. Generally, the fitting attachment must be at least 80 percent as strong as the basic tank material. The final qualification of a crashworthy tank involves the drop test of a complete tank as it would be installed in the aircraft from a height of 65 feet.

Flammable fluid lines must also be protected. They are of a tough, flexible material to resist cutting from crashed, damaged structure and routed along heavier structure which is less likely to deform or fail in the crash. They are somewhat longer than the absolute distance they cover to accommodate potential displacements and are equipped with self-closing breakaway valves. Other fuel system components such as filler necks, quantity sensors, boost pumps, sump drains, fuel strains, and vent systems must be designed the same to maintain tank integrity to prevent spillage in the crash event.

The major technical factor hampering the application of the helicopter technology to the transport aircraft is the lack of a thorough dynamic description of the survivable transport crash. Light fixed and rotary wing aircraft survivable crash scenarios have been established empirically and analytically. They include a description of the dynamic survival envelop and of other factors related to occupant survival mentioned in the Crash Survival Design Guide. In general, it can be said that the helicopter CWFS is suitable for use on transport aircraft to the extent that the transport crash scenario is like the helicopter crash scenario. The transport fuel tanks fall broadly into two categories - integral wing tank and fuselage tank. Since the helicopter CWFS was designed for fuselage tanks it may also be suitable for transport fuselage tanks. However, it seems that the application of crashworthy bladder tanks to integral wing tanks is not very promising.

Air Force and McDonnell Douglas studies show that it would result in very substantial empty weight increase and loss of fuel capacity. But even more importantly, the primary advantage of the crashworthy tank - its ability to tolerate large strains - would not be a particular advantage in a wing tank failure mode. In fact, the entire concept of fuel containment for a crash survivable wing tank may not be feasible in light of crash scenarios which include wing separation or other forms of severe crash damage.

Without test verification it cannot be said that the CWFS installed in the transport aircraft fuselage tanks would be completely effective. It can be said that although it might not be the optimum configuration, it would certainly be a significant improvement over the current bladder tanks, and since this improvement would be realized adjacent to the occupants where crash fire protection is urgently needed, it appears to be an attractive near-term solution. There appears to be two levels of development available. First, the existing bladder material could simply be replaced with a basic crashworthy tank material which satisfies the material properties of MIL-T-27422B. There would be some empty weight increase but true crashworthiness would probably not be gained. Second, the bladder tank would be replaced with a crashworthy tank completely qualified to MIL-T-27422B. This approach would involve selection of optimum lay-up fabrication techniques and incorporation of crashworthy fittings so that the 65 foot drop test could be passed. Naturally, the weight penalty would exceed that of the first alternative but ability to tolerate a crash would be enhanced. The ultimate weight of the crashworthy tank is not simply the basic material aerial density multiplied by the surface area. The tank wall lay-up may vary in thickness to provide the strength necessary during the drop test and to account for geometrical differences. For example, a tall, thin tank will generally be more heavy than a long, flat tank of the same volume because of its orientation during the drop test. Furthermore, the fitting attachments will add varying amounts of weight depending on number and location. Nevertheless, several existing crashworthy tanks were examined and it was found that on the average one pound of tank is required for each 2.9 gallons of fuel. This ratio was used to develop the estimated weight increases shown in Table 4.6. For example, the 727-200B has three optional fuselage tanks currently fabricated from a noncrashworthy bladder material. If this material were changed to a crashworthy material the weight difference would be 615 pounds (Table 4.7). Other potential uses for the crashworthy fuel tank in the center wing/fuselage locations are shown in Table 4.6 with the estimated weights. In addition, all other fuel systems components within the fuselage should be crash hardened by incorporation of breakaway valves and crashworthy lines.

The technology challenge to achieve complete fuel containment for integral wing tanks is immense in view of jet transport crash kinematics. Nevertheless, tank design concepts which may achieve at least partial containment could have such a significant payoff that the approach should not be dismissed. It is time for a fresh look at integral wing tank design for containment and fire prevention. Such a study should begin with a thorough examination of those accidents, in which wing separation and large fuel spillage occurred and did not result in a fire. All factors of the fire chain should be examined in search of a weak link which could be exploited for increased fire hardeness. Tank compartmentation and self-closing valves may be a partial solution to this problem. Schemes to structurally isolate the tank from the main wing structure so that crash failure modes tend to leave the tank intact may be another.

TABLE 4.6 - FUEL SYSTEM SIZE/WEIGHT SUMMARY FOR SOME JET TRANSPORT AIRCRAFT

AIRCRAFT MODEL	kg EMPTY WEIGHT	kg MAXIMUM T.O. WT	kg MAX ZERO FUEL WT	kg MAXIMUM PAYLOAD	ℓ FUEL CAPACITY	kg CRASHWORTHY TANK WT (1)	kg CRASHWORTHY TANK WT (2)
747-200C	155,598	362,880	238,594	66,758	193,035	7,977	2,609 (3)
737-200C	28,627	52,391	43,092	14,465	19,497	806	
727-200B	44,906	83,462	62,597	17,690	40,371	1,668	279 (4)
707-320B	64,003	151,321	88,452	24,449	90,291	3,731	1,564 (5)
DC-9 SER 40	25,261	51,710	42,185	15,511	13,925	576	
DC-10 SER 30	121,225	251,748	166,925	47,401	135,503	5,600	2,190 (6)

(1) Estimated weight increase to add a crashworthy tank material now used on helicopters to the entire fuel system of the jet transport.

(2) Estimated weight increase to add a crashworthy tank material to center wing or fuselage tanks only.

(3) Center wing tank only.

(4) Optional fuselage tank only.

(5) Center main tank only.

(6) Auxiliary center wing only.

TABLE 4.7 - BOEING 727 OPTIONAL FUSELAGE FUEL TANK WEIGHTS

TANK NO.	(ℓ/GAL) CAPACITY	(kg/lbs) BLADDER WEIGHT	(kg/lbs) CRASHWORTHY TANK WEIGHT (1)
1	2051/542	15.8/34.8	84.4/186
2	3456/913	23.2/51.1	145.6/321
3	2600/687	19/41.8	106.6/235

(1) Estimate based on direct replacement of existing bladder with a crashworthy tank material now used on helicopters.

4.2.3.3.2 Antimisting Fuel

Another method to reduce the post-crash fire problem is fuel modification to reduce its crash fire potential. The only modified fuel now under advanced development is an anti-misting fuel made by adding FM9, made in the United Kingdom by ICI Limited to Jet A - Kerosene Fuel. The additive makes the viscosity of the base fuel a function of shear rate so that its tendency to atomize or form a spray in a crash impact is reduced. (Reference 4.7.6, 4.7.7 and 4.7.8)

Anti-misting fuels containing a polymeric additive have been shown to be effective in preventing mist fires for simulated crashes for fuel temperatures up to 25-29°C in 80 mph crashes and up to 23°C for a 130 mph crash. Study of fuel loading temperature statistics suggest that such situations will cover over 90% of severe crashes. Several types of additive have this property of fire resistance, but only FM9 is being developed for civil use because this particular additive offers the best compromise between fire resistance and system problems and, as the additive contains only the elements carbon, hydrogen and oxygen, no environmental pollution is envisaged. The fire resistance of FM9 has been demonstrated on a number of tests in the United Kingdom and United States including engine ingestion tests. The engineering feasibility of FM9 has been demonstrated in a number of areas, low temperature pumping and absence of any precipitation of the additive at low temperatures; an 8 hour engine test, including restarts, at NGTE showed, with sufficiently pre-degraded AMK, that engine performance was indistinguishable from AVTUR and similarly successful results were detailed in a simulated 2 hour cruise in a BAC 1-11 low pressure fuel system. (Reference 4.7.9)

The tests have shown, however, that there are a number of problem areas. The engine test at NGTE and subsequent engine simulator tests have shown that degraded fuel is required for a satisfactory filter flow performance, servo-response, etc., and intentional degradation of the fuel is a major area of investigation. Although chemical degradation has been shown to be possible, from environmental and other aspects, a single pass mechanical degrader is preferred. Such a device has been demonstrated (reference 4.7.8) on a small scale and appears promising, performance wise, as well as being capable of being incorporated within the engine backing pump. Efforts are continuing to scale up this device to match realistic engine flow rates and to try to improve the efficiency. Such a device, if successful, will alleviate the problems in filtration, engine control systems and heat exchangers, the latter due to the reduced heat transfer coefficient of undegraded FM9.

The intention is for FM9 to be blended with the kerosene in the refueling line to avoid blended fuel ground handling problems. The feasibility of this method has been shown with FM9, a feature which does not apply to all additives, it having been demonstrated at RAE that on a small scale it is possible to blend the additive with kerosene and successfully pass the test on the RAE rocket track for fire resistance within 15 minutes of its preparation.

The further development of such a mechanical degrader and a blending method is the priority aspect of the United Kingdom's work in the immediate future.

The BAC-11 system test (reference 4.7.9) showed there to be no serious operational problems from the aircraft manufacturers viewpoint although one new phenomenon did emerge; this was the formation of gel within some components. It is possible that this fact could have been aggravated by the age of the fuel used (a situation that will not arise with in-line blending). This is a problem that will need further investigation with representative fuel although methods of alleviating the problem are at present under consideration.

Degradation of the fuel occurred in the transfer system, within the tanks at one or two time periods of simulated flight, to such an extent that it was considered that the fuel sampled was marginally acceptable from an anti-misting aspect; however, it is considered that sample system modification could considerably relieve this level of degradation.

A problem of water incompatibility may exist and tests are being made to assess this in a practical condition. However, it is certain that large scale ingestion of water during refueling would cause problems.

In the United Kingdom the main priority areas for investigation are mechanical degradation and in-line blending, no further large scale engine or systems tests are planned but work will continue on investigations into possible gel formation and water incompatibility. A collaborative program between the United Kingdom and United States is currently being planned and discussed. A large amount of work remains to be done with FM9 before full-scale flight testing, leading to certification for civil use, can be envisaged although a number of problems remain they are not thought to be insuperable. The introduction of AMK will require fuel system modifications, possibly on a retrofit basis.

4.2.3.3.3 Fuel System Fire Hardening and Explosion Protection

Major leakage can also be caused by a breach of fuel system integrity other than wing separation. Such failures can be caused by landing gear collapse into fuel tanks or lines, engine separation and tank damage from impact with obstacles. The recent rash of tire failures indicates that even this apparently minor failure mode can initiate a catastrophic fire chain. The broad nature of potential threats makes identification of specific interdictive measures difficult. Nevertheless, overall design practices and application of materials can minimize the potential for aircraft self damage, increase damage tolerance to obstacle impact and reduce the potential for ignition.

Accident experience indicates that the fire scenario involving post-crash fuel tank explosion is a significant threat to occupant survival. In this scenario the explosion of an intact fuel tank is precipitated either by pool fires which locally heat the fuel tank surface or by flame propagation through the vent into the ullage.

Two potential interdictive measures exist. Testing has shown that if the ullage oxygen content is below 10 volume percent, explosions will not occur (reference 4.7.11). Consequently various systems to dilute the oxygen with nitrogen may be effective in preventing this failure mode. In recent years design studies have been conducted to evaluate the potential use of nitrogen inerting systems for transport aircraft (reference 4.7.12). The second measure would involve fire hardening of the fuel tank to increase the fire exposure time required to initiate the combustion reaction.

The nitrogen gas source can be provided from a stored container on the aircraft or generated in flight by a separate subsystem. Design studies indicate that storing the nitrogen as a cryogenic liquid is the most efficient of the storage systems. The basic system is simply a Dewar of liquid nitrogen interfaced with the fuel tank through the necessary control units to provide a regulated amount of gaseous nitrogen. The specific design requirements are heavily influenced by the selected mission profile, level of inerting required, in-flight fuel management, and, to some degree, the method of introducing the nitrogen into the tank. A system is now in operation on the C-5 fleet. If protection were desired only during the landing phase a very low penalty system may be possible.

The on-board inert gas generators which have been investigated are of three major types - sorbent bed, catalytic reactor, and membrane separation. The sorbent bed system is based on oxygen absorption from air by a metal chelate, fluomine. The catalytic reactor system generates inert gas through catalytic oxidation of the jet fuel. The membrane separation system used semipermeable membranes to separate the major constituents of air into oxygen and nitrogen for inerting. A design study is described in reference 4.7.13 which examines the application of this technique to a DC-10 aircraft. At this stage of development it appears to have significant weight, logistic and cost advantages over other inerting systems for air transport use. Design studies indicate that a system for use on the DC-9 aircraft would weigh about 360 lbs.

The technology is available to bring any one of these systems into operational use in the next five years. They all impose sizeable aircraft performance, operational, and - for liquid nitrogen - logistical penalties. However, the military continues to improve these systems for inflight combat protection and may in the near future develop a low penalty system more suitable for air transport use. So, while current generation of inerting systems does not appear widely acceptable for air transport use, spin off from military development may provide a more acceptable system.

A second category of potential interdictive measures to limit the post-crash tank explosion involves the use of materials to fire harden the tank.

Void filler foams, intumescent coatings and paints could be selectively applied to reduce the heat transfer rate to the tank and delay or prevent catastrophic explosion. The polyurethane foams have demonstrated the ability to significantly reduce heat transfer into an intact aircraft fuselage within a pool fire and could be used in a similar manner on aircraft wing void spaces. Where space or weight limitations are encountered the intumescent coatings or paints should be effective. Application of these materials directly to the fuel tank walls should be investigated.

Where external fire hardening materials are used the ullage will be vulnerable to ignition by flame propagation through the vent. Complete protection could be achieved through the use of a flame arrestor in the vent. The flame arrestor material would have to be tolerant to the high temperature environment or protected from it by design.

4.3 Airframe and Other Systems

4.3.1 Airframe, Structural Considerations

According to the findings of Subgroup I, the main fire threat stems from the fact that fuel is released during and after wing separation when the aircraft crashes.

Although at present no data could be derived from the accident data regarding a typical failure mode of the wing, structural analyses could indicate where wing fracture will likely occur when a rearward shear load is applied. If such a location can be indicated the inner wall (closest to the fuselage) of the wing tank should be constructed such that this fuel will be contained during a crash.

The next major threat appears to be fire resulting from ignited fuel released as a result of damaged tanks and lines.

Application of the presently available crash resistant fuel tanks, at internal fuselage locations would prevent fuel release close to or in the fuselage. In addition, careful design of the center wing section or the area surrounding the tank is desirable to avoid structural features which could puncture internal mounted tanks. Location of the tanks should be such that abrading action of the lower side of the belly on the ground and interference with small objects during the ground slide will not rupture the tank.

4.3.2 Landing Gear, Structural Considerations

Failure modes have occurred where a main gear failure has resulted in a tank rupture with fuel spillage onto hot parts and a subsequent fire. This scenario often occurs when the aircraft leaves the runway and strikes various irregularities in the terrain.

The landing gear design, in particular the failure mode following overload in the rear and sidewards direction, should incorporate a "weak link" in order to avoid rupture of tanks.

4.3.2.1 Ignition Control

Maximum brake energy absorption is called for during a rejected take-off or a fast and long landing. The resulting elevated brake temperature constitutes an additional potential ignition source.

The aforementioned "weak link" in the landing gear, causing a timely break-away of this ignition source would also serve the aim in preventing ignition. When the landing gear remains intact during a major crash-landing or an otherwise abnormal condition during operation, landing gear fires could be initiated as a result of tire failures, overheated brakes sometimes accompanied with leakage of hydraulic fluid.

Tire failures could result when the aircraft is in the process of taking off or landing with under inflated tires. Information of real time tire pressure to the cockpit could prevent an aircraft being dispatched with improper inflated tires or provides the possibility for timely alert of the fire-fighting unit of an airport. Brake temperature indicators of an overheat detection and warning system in the cockpit could prevent the aircraft taking off with overheated brakes which could seriously impair the rejected take-off performance or result in an overheated landing gear well after retraction. Restriction of hydraulic fluid loss on hot spots (as brakes) can be achieved by installation of hydraulic fuses at proper locations.

Aircraft belly materials should also be selected with low sparking characteristics when being abraded on the runway during a wheels-up landing.

4.3.3 Electrical System

Main power cables must allow for deformation and stretching without failure in case of a minor crashlanding. Other cables which can produce an ignition source when separation occurs in the vicinity of flammable material must also be taken into account.

Together with fuel cock shut selection (as a part of the emergency procedures) all electrical power, servicing components in the wing, should be switched off automatically to prevent continued operation of fuel booster pumps, landing lights, strobe lights, etc., in order to avoid any electrical ignition source during a crash-landing.

4.3.4 Environmental Protection

The main purpose would be to enhance the available evacuation time when a fire occurs. The following measures should be considered:

4.3.4.1 Built-in Fire Detection and Extinguishing System

These systems should be able to withstand at least the inertia loads as specified for a minor crashlanding to safeguard operation after such a landing.

If fireproof properties of these system can be achieved they should be installed as such.

4.3.4.2 Windows

Consideration should be given the application of, presently available, fireproof window material to optimize isolation from an external fire.

Local application of fuselage skin fire hardening adjacent to the emergency units could prove a barrier providing the occupants more time to escape.

Evacuation slides which currently are not designed to have fire resistant properties should be developed to have properties to withstand radiation heat or otherwise be fire resistant.

4.3.4.3 Electrical System

Cables where high power could exist normally or during failure conditions (e.g. main power cables and cables servicing the HF antenna) must be isolated from flammable fluid lines or provided with adequate shrouding.

All main or high power cables must be designated such that deformation and stretching is possible without failure at locations where such a failure could be a potential ignition source.

4.3.5 Ventilation Management/Control

It is important that when an inflight fire occurs the cockpit crew will be able to make an emergency landing. This implies that the cockpit should be free from smoke obscuring the instruments.

In order to maintain a good view in the cockpit there should be no smoke migration from any area of the pressurized fuselage to the cockpit. This can be achieved by providing a constant overpressure in the cockpit either as a normal design criteria or by means of adjustable ventilation shut off valve decreasing the air mass flow to the cabin.

Best pressure distribution would be an overpressure in the cockpit compared to the cabin and the underfloor section.

4.3.6 Design Considerations, Non Contained Engine Debris

As a contained engine failure cannot be assured, the location of the engines in relation to the fuel tanks must be considered at an early stage of the design.

In addition the routing of fuel lines and/or proper drainage of the fuel to ambient in case of a fuel line rupture caused by engine-debris should be provided.

4.3.7 Alert and Fire Suppression System

These systems must possess fire resistant properties (incl. retaining their functional capability) where the wiring and components are adjacent to fire zones and must be developed to be fireproof when in fire zones.

If inflight fire risks exist in non accessible areas of the fuselage considerations must be given to installation of an early warning detection, monitoring and fire suppression system (at the present the aerosol detection method and the use of Halon 1301 appears the most promising).

For non-occupied but accessible area a warning system would be sufficient provided that manual suppression is the effective method.

A suppression system integrated with the above mentioned system, serving the occupied areas as a whole, could be taken into consideration after development of an acceptable life support-hood for the occupants.

4.4 Aircraft Interiors

4.4.1 Background

Aircraft passengers are virtually captive to the aircraft system. Escape is almost impossible if emergencies occur when the aircraft is moving, whether on the ground (taxiing) or in flight. Passenger safety, therefore, is a system safety problem that is dependent for example, on human factors, such as pilot error and passenger stress; on design factors, such as the hydraulic system and extent of fire resistant construction; on navigational aids, such as on-board or ground-based radar; on fire fighting equipment, such as on-board fire extinguishers and ground fire fighting equipment and procedures; and on the weather. In short, safety is the interaction of many and often complex components, and each should ensure maximum performance within design constraints.

This report is focused on a limited area of safety in this overall system - the fire safety of state-of-the-art materials used in aircraft interiors and the development of compliance and screening tests for such materials.

4.4.2 Present Fire Safety Requirements for Cabin Materials

The Federal Aviation Administration (FAA) has the mandate for aircraft safety and regulation in the United States and international regulations are very similar to the FAA regulations. Since 1946 the U.S. Government, through its agencies, has regulated the flammability of materials allowed in aircraft compartments. Initial regulations were written to include installation of materials that were "flash resistant." Essentially, this regulation specified only a control of the rate of flame spread. In later years the regulation was changed to include only those materials that were "flame resistant."

In 1972 the compliance tests to prove that materials were "flame resistant" defined flame resistant as meaning that the materials were "self-extinguishing" over a certain length, in either a vertical or horizontal configuration, after ignition by a prescribed ignition source.

Although these materials are called self-extinguishing and can pass these flame-resistant tests, they are still combustible. In larger scale tests by the FAA, NASA, and others, many of these materials have been shown to burn under certain conditions. Under severe fire conditions they can even contribute to the fire as fuel because they are organic materials and organic materials are fuels by virtue of their molecular nature. The small and large-scale tests conducted by FAA and NASA do prove, however, that the materials that pass the present compliance tests are harder to ignite than previously allowed materials, thus lessening the probability that ignition will occur and that flames will spread.

In 1966 the FAA also suggested that it would be feasible to regulate the allowable emission from cabin materials, thereby improving the probability of maintaining control of the aircraft and of subsequent evacuation. In 1969 the FAA gave notice that it proposed to develop smoke emission standards. In 1975, after review, FAA smoke emission compliance tests were reported. Still, at this time, no FAA smoke regulation exists because of technical difficulties. Similarly, in 1974 an FAA notice to establish toxic gas emission standards for interior compartment materials was given, but they, too, have been delayed. Therefore, only a flammability regulation exists; no smoke or toxic gas emission standard and compliance test exists at this time. Some of the difficulties that may have postponed these regulations are inherent in requirements necessary to develop such standards. Why is such a standard necessary? What must be included in such a safety standard? How can we test that the safety standard will be met?

There is also always the question of even wider ramifications of such regulation. Regulation often means additional cost and cost affects the feasibility of retrofit. Moreover, regulations can dictate the development of a new, sophisticated, and expensive technology, one that can produce a low-smoke, low-toxicity, low-flammability, wear-resistant, lightweight, structurally sound, material at reasonable cost. Most of the state-of-the-art materials used in aircraft interior are synthetic materials and are used on other applications; therefore, the same materials' problems can arise in other transportation and building construction application - especially so because the market is expanding in these areas. Any regulation of aircraft materials can result in regulatory counterparts in these other applications, thus restricting the number of products allowed on the market. As a result, any solutions of the fire, smoke, and toxic gas problem considered for aircraft interiors may have far reaching economic consequences in the chemical industry. This in itself would be a suitable subject for an entire study. Therefore, the fire problem is very complex. This report is only intended as a limited survey of information in a rapidly changing field of fire safety.

4.4.3 The Nature of the Fire Threat

In nearly 25 percent of commercial transport accidents, fires ensue. A recent study shows that 69 percent of these fires occurred on the airfield, 19 percent on the ground but off the airfield, and 12 percent during flight; that is, most of the fires occurred where fire fighting equipment was available. Most of these fires - 70 percent - are fuel fires that start after a crash, 20 percent start in engines or wheels, and only 10 percent within the airframe in such areas as lavatories and cargo bays.

The degree to which injuries and death are caused by impact as distinguished from those caused by fire is not well defined. In many accidents, structural evidence is obliterated or the results of autopsies are not available. Some evidence, however, has been obtained and it has been used to make an estimate: that estimate attributes approximately 20-32 percent of the deaths in aircraft accidents to fire alone.

In the period 1952-1972, according to this estimate, fire caused the loss of about 1000 lives. Impact-survivable accidents, which are occurring in the United States at a rate of about one or two a year, provide description evidence of the types of fires and of the ensuing cabin conditions that can occur. Passengers have found it difficult

to get out of the cabin, and smoke and toxic gases - in addition to the intense heat - have made it difficult for pilots to control their aircraft. Again, it is difficult to differentiate to what extent death, injury, or loss of aircraft control are caused by heat, by oxygen deficiency, or by smoke and toxic gases that jet fuel, clothing, luggage, and/or cabin materials may give off.

Substantive evidence may be forthcoming from the FAA, which has begun to emphasize forensic toxicology with regard to cabin materials' effects in accident investigations. Limited autopsy findings in these accident investigations show that carbon monoxide and cyanide are in the victims' blood. Although clothing, luggage, and fuel pyrolysis might also contaminate the cabins with these compounds, it has been proved that cabin materials emit smoke, carbon monoxide, cyanide, and other toxic gases on pyrolysis.

Flash fires have also involved cabin materials. Therefore, though it is not known to what extent these materials are at fault, they must still be considered as a potential cause of injury, and their relative smoke and toxic gas emission and their fire resistance should be compared and evaluated.

4.4.3.1 Materials' Testing

A materials' fire safety standard and test for materials for aircraft interior compartments must address itself to the types of potential fire hazards and to the frequency of their occurrence if we are to understand why and how these materials are involved in the fire scenario and how they should be regulated and tested. Compliance tests should, insofar as possible, simulate accident conditions. Therefore, an analysis of the nature of the fire threat is necessary.

The fire accident types mentioned earlier were classified as originating in three ways: (1) the crash fuel fire, (2) airframe compartment fires, and (3) the engine and wheel system fire. With time, fire propagation may cause fire to spread from one to another of these areas. For a full understanding of the fire threat the response in each of these fire accident types should be obtained. However, in this limited analysis only crash fuel fires and their effects on cabin materials will be considered because they are the most common cause of fire. Recent studies of impact-survivable accidents have shown that in most cases cabins were set afire by flames originating from a large external fuel fire that entered the cabin through a rupture or through open doors, while the remainder of the fuselage was otherwise intact.

4.4.3.2 The Crash Fuel Fire

In full-scale crash and fire tests, fuel tanks and lines rupture after impact and the rapid deceleration that follows, and fuel may be dispersed as vapor, fine mist, or as large aggregates surrounding the aircraft. When the aircraft slows sufficiently, the remaining fuel may be spilled to form either a pool on the ground or to seep into the ground if soil conditions permit.

The fuel may then be ignited by an engine fire, by engine ingestion and flash-back, by hot engine surfaces, by friction sparks, or by electrical arcing or sparks. When ignition occurs, both fire and explosion can result. Depending on the severity of the impact and on the extent of structural damage, fuel may or may not enter the passenger cabin to cause full-scale fuel fires within the compartment. In tests by the FAA, both possibilities have been observed. Temperatures and heat fluxes of the external fire may be of the order of 1106-1384°K (1500-2000°F) and 3-12 Btu/ft^2/sec (3.3-13.2 W/cm^2) and can last for 10-30 minutes, covering an area of 464 m^2 (5000 ft^2). Survival times under these conditions have been estimated to be 1-5 minutes when the fuselage remains intact but only 1 minute when the fuselage is ruptured or when escape hatches are opened. Survival times are nearly equivalent to the times required for evacuation. In other words, few survive who remain in the aircraft.

In view of these fuel fire data, it can be estimated that a typical crash-survivable accident would be characterized by the following:

(1) A crash on an airfield where fire fighting equipment is available in a few minutes.

(2) A large external fuel fire.

(3) Flux levels of the order of 3.3-13.2 W/cm (3-12 Btu/ft^2/sec) and temperatures of 1106-1384°K (1500-2000°F).

(4) Burn times of 10-30 minutes.

(5) Cabin ignition or decomposition by fuel fire.

(6) Survival times of the order of 1-5 minutes - nearly equivalent to actual times with present aircraft designs.

4.4.3.3 The Effects of the Crash Fuel Fire

In a crash fuel fire with the flux and temperature levels noted above and the fire widespread around the aircraft, the aluminum skin on the fuselage will melt in about 60 seconds causing loss of structural integrity and almost immediate exposure of the interior to the fire. Thus when a major rupture in the fuselage occurs on impact or when the fire nearly surrounds the aircraft, death and injury - primarily associated with the fuel flames, gas and smoke penetration causing direct burns, and with thermal shock and toxic effects - will occur in a very short time relative to the time required to evacuate the aircraft. Improvement of cabin materials in their present configurations will have little benefit in this fire scenario. (No estimate of the relative occurrences of this type of accident has been made but certainly it is of prime importance.) Rather for the severe fire case other methods such as fire curtains, fuselage insulation, fire areas, or ground fire fighting equipment, etc., would be appropriate for development.

A test system associated with the relative safety of interior materials should therefore only include the limited cases in which a minor flame ignition source is involved or in which only external heating of the cabin volume occurs. (This condition is also similar to that of a fire in an airframe.) By minor ignition source is meant one which does not of itself, by virtue of gas or smoke toxicity, significantly degrade survivability within the cabin for evacuation times of 1-5 minutes and during burn periods of 10-30 minutes. Figure 4.1 is a sketch of an aircraft subjected to these limited fuel fire conditions. Let us examine a section of the aircraft A subjected to a fuel fire B. As shown by corresponding numbers in Figure 4.1, this volume is subjected to: (1) Intrusion of flames to act as an ignition source in A; (2) A heat flux due to the external fire around the fuselage; (3) Influx of fresh, cooling and oxidizing atmospheres from other areas; (4) Transfer of combustion atmospheres and heat to other areas; and (5) Cooling in other areas.

Passengers will normally move away from the area A in order to escape immedate injury. Area A, however, remains a source of danger due to the phenomena cited in item (4) above. How fast area C reaches thermal and/or atmospheric thresholds for survival or evacuation, is a test of the relative materials' safety.

It is not clear a priori which phenomena will cause the cabin to reach the thresholds quickest. For example, if A to C is considred completely adiabatic and closed, specific concentrations of heat and toxic gas may or may not be reached quicker than if a fresh supply of oxidant due to open escape hatches or to a chimney effect increased the burning rate and gas generation rate. The influx of air may also dilute or change the toxic gas concentrations and reduce oxygen deficiency and smoke. This implies that the system is too complex to overly simplify or to eliminate variables and still expect a proper test system. Because of the number and complexity of parameters in the system, a method should be derived at to examine their interactions dynamically. One such method is application of a fire model.

4.4.4 The Fire Model

A fire model for the cabin can be developed as a management aid so that it emphasizes what laboratory data can be obtained that adequately describes the interactions in the cabin environs. The inputs to the model should be outputs from the laboratory tests. The FAA is now developing a sophisticated model of the heat, mass and kinetic processes in the cabin. NASA has developed a model for spacecraft and, though simplified, it is exemplary for the case in point. The model is a management tool - a more thorough understanding of the critical development of separate compliance and screening tests in the laboratory.

In the NASA model, the model performs an unsteady state accounting of both heat and mass transfer in and out, generation of heat and mass within, and heat conduction in or out through the walls. Provision is made so that the decompositon of materials can be related to the thermal conditions of the wall or to the atmospheric thermal conditions within the cabin.

The thermal balance on a man within the chamber can also be made, to predict the effect of heat on his metabolic state, thus providing a measure of this thermal threshold. Since the concentrations of toxic constituents are available as a function of time they can be related to symptomology reports in the literature. Some synergistic effects of heat and toxic gas may be calculated with the model because of the thermal effects on circulatory and breathing rates, and vice versa. Thus, as a guide, one of the first components in the development is a model that can be used to emphasize areas and properties of the required data base.

4.4.4.1 Heat and Mass Transfer Properties in the Test Chamber

Large-scale tests provide essential data but they are costly. Laboratory tests, which are fast and less expensive, are a preferred alternative. In

designing a test chamber, an effort should be made to simulate the conditions in our simple aircraft model in the volumes A-C. Thus the laboratory chamber should provide for:

(1) Weight to volume ratios for sample tests similar to aircraft.

(2) Flame ignition.

(3) Thermal levels to 12 Btu/ft^2/sec.

(4) Test times to 30 minutes.

(5) Mass and heat transfer characteristics similar to those of the aircraft structure.

The first four properties may be easily obtained by a suitable choice of equipment. The last required further review because the different phenomena have not been defined.

The time necessary for convective heat and mass transfer may be important from area A to C in determining critical threshold times for aircraft evacuation and survival. Therefore, the laboratory chamber should try to scale times with regard to transport processes in the aircraft and chamber. Normally, an escape hatch is opened or a rupture in the fuselage occurs. Depending on the location of the openings, a chimney effect may be produced by the heated gases. It can be calculated that this effect can result in velocities of toxic variables of the order of several hundred feet per minute. Even natural convection currents of oxidant due only to heated surfaces are of the order of 100 ft/min in a closed system. Wind speed is another potential source of convection; a 5 mph wind represents several hundred feet per minute in convective flow. Aircraft dimensions are of the order of 10 to 100 ft; this means that test chambers should have linear times between areas in the chamber of about 1 minute.

Stratification is another phenomenon that occurs in the fire scenario. Gases are notoriously bad mixers. In a closed aircraft system, however, the seats may act as baffles to improve mixing. A test chamber here should have the property of a completely mixed system. In the system where the stratified layers are retained, mixing would be by diffusion, with mixing times of the order of 1 hour, or times in excess of the fuel fire history. In these cases evacuation times may be adequate if no other phenomena occurred, such as spreading of the fire. Therefore, such a case would not be important; passengers would avoid the toxic gas effects by crouching in areas where the gases had not orginated or become stratified.

A test chamber might not have to include this case. In another case massive gas generation would occur causing displacement or plug flow from area A to C. In such a case the velocity is closely related to the molecularity and to the gas generation rates or kinetics of decomposition of materials; the velocity would, therefore, vary with the type of weight of materials decomposing and with the temperature history of the environment. A test chamber here would provide for variable thermal environs and should provide for some measure of the rate of loss of materials. For simplicity, smoke and gas effects are separated from thermal effects in most laboratory tests.

Thermal effects are not considered in conjunction with these effects, and no synergistic effects are noted. Instead, separate calorimetry and flammability tests are performed to measure the thermal contributions. Although these may identify when materials contribute thermal energy, they do not relate to the net heat balance in a cabin volume or to the heat transfer and thermal threshold in the aircraft. Use of the model would help relate these separate effects to the aircraft condition, but test chambers that could be maintained at elevated temperatures would be even more appropriate.

4.4.4.2 Test Chambers Currently in Use

Laboratory test systems are now under development that may be used in running compliance tests. The following listed systems show some of the variations in design being considered.

The NBS Chamber - a 3 in. x 3 in. sample of material is irradiated within the chamber and degrades. Flux levels are about 2.5 W/cm^2. A small flame ignition source is also available. Smoke obscuration is measured with a light and photosensor (optical density) as a function of time. Gas concentrations are measured within the chamber. This is by far the most popular system and is commercially available.

NASA, Ames Chamber - The water cooler chamber contains a continuously weighed sample of up to 1 lb or 12 in. x 12 in. The sample is irradiated through a window by an electrically powered panel. Flux levels can be varied continuously from 0 to 5 W/cm^2. Purge gases can flow into the plenum. Seven mice are placed in he rate cage for biological testing. Gas concentrations are monitored. A filter sample of aerosols or dusts with diameters of 0-5 can also be obtained from the chamber. Provision for a small flame ignition source is located in the chamber.

DuPont Test Chamber - This test facility is a two-stage system with biological testing. Here only an ignition source is used to decompose flammable materials in one chamber and the pyrolysis gases recycled to the biological chamber. The above descriptions are brief and also do not present many other excellent systems such as those developed and used at the Armstrong Cork Company, etc. They do, however, represent a cross section of the types of lab tests that generate existing data, available to analyze.

4.4.4.3 Large-Scale Tests

Large-scale tests are also available. These are instrumented mockups of actual cabin configurations including fabricated end-items such as seats, carpeting, and panels. Thermal, gas and smoke conditions are monitored. Both FAA and NASA have run fire tests in these systems on present and advanced aircraft materials.

4.4.5 Cabin Survivability

The convective and thermal conditions to which interior materials may be subjected in a crash fuel fire have been previously cited. When the materials are subjected to such conditions they decompose to produce heat, smoke, and toxic gases. When the thermal and toxic effects reach limiting thresholds, evacuation and survival limits are reached. Test methods should monitor these effects to determine the thresholds. Decomposition of these materials can produce:

(1) Changes in the thermal environment.

(2) Reduction in the oxygen content of the atmosphere.

(3) Toxic gas and smoke.

(4) Smoke obscuration.

(5) Explosivity (flashover).

(6) Spread of flames (flammability).

4.4.5.1 Thermal Thresholds

The generation of flames and heat can effect survivability; for example, burns to more than 50 percent of the body are usually fatal. Thermal shock caused by exposure to high temperatures can also cause death or injury. Heat thresholds for periods of time less than burn times of 30 minutes are shown in Table 4.8.

Heat thresholds are also dependent on stress, air flows, etc., and the ability to evacuate the aircraft may be degraded long before tolerance limits are reached. More conservative limits are a temperature of 145°F, the point at which tissue changes occur or a body heat content of 400-700 Btu, the point where impairment of bodily functions occurs. These limits can represent a region where evacuation still possible by sensory perception, etc., may begin to decrease, reducing the probability of escape.

4.4.5.2 Oxygen Deficiency

A lowered oxygen content in the cabin caused by combustion can result in impaired physical response to the evacuation effort. Table 4.9 lists the physiological effects at different oxygen levels. A 17 percent oxygen level is a conservative limit for evacuation and survival.

TABLE 4.8 - HEAT THRESHOLDS

Temperature, °F	Exposure Time, min	Effect
220	25	Maximum that can be tolerated
248	15	Maximum that can be tolerated
284	5	Maximum that can be tolerated
300	--	Limit for escape, mouth breathing difficult
320	--	Rapid unbearable pain (dry skin)
360	0.5	Irreversible injury (dry skin)
390	4	Maximum tolerated (wet skin)
390	4	Maximum tolerated by respiratory tract

4.4.5.3 Toxic Smoke and Gas Emissions

A vast number of toxins, which may impair physical response to evacuation attempts, may be generated by fire, and they make the analyses both difficult and time consuming. Some toxins are more important in this regard than others. Each material decomposition mixture should be treated as an individual case; ratios of toxins may change from one thermal or oxidizing atmosphere to another. Threshold symptomology similar to oxygen effects, listed previously, appear in the literature for many toxins, but often test data do not exist (see Table 4.10). Gas analysis can help determine which toxins are present and whether improved materials are eliminating toxins. More meaningful data would include, beside gas analysis, biological testing. Although there is always some problem in extrapolating animal test results to man, biological testing with mice or other animals can be used to determine approximate times to incapacitation, or chronic effects due to single gases, aerosols, or synergistic effects of gases in the mixtures. For example, some data suggest that toxic effects occur at lower concentrations of CO and HCN in a mixture than for the pure gases. Because single threshold limits for gases are not indicated, the total biological effects should be studied. This approach will further ensure that pyrolysis mixtures are safe or that extrapolations can be made from one condition to another.

TABLE 4.9 - PHYSICAL EFFECTS ASSOCIATED WITH O_2 LEVELS

Oxygen, %	Effects
21	None
17	Impaired muscular coordination
14	Danger level for self-escape
12	Dizziness, headache, rapid fatigue
9	Unconsciousness
6	Death in 6 to 8 minutes

TABLE 4.10 - EFFECTS OF HCL ON HUMANS

Concentration, ppm	Exposure time, hr	Symptoms
6.6	Prolonged	Harmful
8.6	6	Tolerated without noticeable symptoms
50-100	Immediate effect	Work is impossible
990-1320	0.5-1	Dangerous to life
890-1720	0.5-1	Fatal in a few minutes
3630	Immediate effect	Immediate death

4.4.5.4 Smoke Obscuration

Smoke obscures escape routes and otherwise makes escape from the aircraft more difficult. The measurement of light transmission is one way to determine the extent of obscuration. The light transmission required to make lighted exit signs visible varies over a wide range depending on such factors as the general illumination level, the extent to which the observer's eyes have been dark adapted, and even on the irritating nature of the smoke. Limits for visibility have been reported that range from 2.5 to 80 percent light transmission. The FAA is considering smoke obscuration limits that represent about 2.5-15 percent light transmission.

4.4.5.5 Explosivity

Explosivity or flashover phenomena are not totally understood. At some point in the life of a fire contained in a given volume, flame can so rapidly fill the entire volume as to be a virtual explosion. Until further study, it is difficult to assign a threshold for these phenomena. Although some researchers use the time to reach 500°C as a measure, this does not in itself reflect on the reasons for or the approach to flashover condition. Explosivity may have more to do with a gas explosion limit, the existence of which is determined by a combination of heat, mass, and kinetics that help create the limit. Therefore, like the toxic gas problem, the limit is more particular to the system properties together rather than to an individual property.

4.4.5.6 Flammability

The spread of flames from one area to another can contribute to all of the above phenomena. Therefore, tests on the flammability or flame-spread characteristics of materials, like the FAA tests of self-extinguishing limits, are necessary. These tests should probably be augmented by the full-scale tests on end items that the FAA and NASA have devised.

A summary of these hazards and remedial safety design is shown in Table 4.11. It can be seen from the table that a common method of reducing each hazard is to develop new materials with fire hardened properties.

TABLE 4.11 - HAZARDS REVIEW AND SAFETY DESIGNS

Hazards	Potential Safety Designs
Thermal	(1) Reduce flammability of materials
	(2) Isolate flammable materials
	(3) Provide for quick fire detection and extinguishment
	(4) Divert convective flows
	(5) Provide thermally insulated safe areas
Oxygen Deficiency	(1,2,3,4) above
	(6) Provide air reservoirs
Toxic smoke and gas	(1,2,3,4,6,) above
	(7) Reduce materials' smoke and gas generation
	(8) Provide goggles and gas masks (limited, not effective for all gases, e.g., CO)
Smoke obscuration	(1,2,3,4) above
	(8) above (limited, only reduces eyes irritation, not optical)
Explosivity	(1,2,3,4,5,7) above
Flammability	(1,2,3,4,5) above

4.4.6 Review of the Existing Data

By far the largest amounts of data have been obtained with the NBS test chamber, the FAA fire resistance test, and calorimetry. Many hundreds of materials have been tested and all cannot be reviewed here. Because paneling covers almost all the interior walls and ceiling of most aircraft, its smoke and toxic gas generation characteristics as determined by the NBS tests will be reviewed here. This paneling is also the first interior material, after some external glass insulation, that separates the interior cabin volume from fuel fires originating outside the fuselage. Therefore, it can be the first compartment interior material to experience high temperatures.

An effort in the industry has already been made to synthesize new materials with fire hardened properties and as such is an attempt to advance the state-of-the-art. A comparison of these materials with state-of-the-art materials will show to some degree the feasibility of producing fire safe materials. In addition, some data from large-scale tests of a mockup compartment that included pre-1978 and advanced materials will be reviewed.

Figure 4.2 shows a typical smoke and gas concentration history from the NBS test, for a panel presently flown on some aircraft. Table 4.12 shows NBS chamber data for maximum values, for about a 7-min burn. Some advanced materials are also included. Reviewing the NBS data emphasizes there is a lack of consistency in the type of information available and only a limited degree of success in materials' development. Problems arise in the data base because complete gas analyses are not run. One laboratory will run one set of analyses and another laboratory will run a different one. There is also the possibility that reproducible results are not obtained by different laboratories. In other words, there is an evident need to improve and standardize.

Let us further examine the data for the NBS chamber, with appropriate apologies for linearly extrapolating the data to our simple aircraft model. The case we choose is that of plug flow from A to C. The composition in A is assumed uniform and equal to the maximum data reported for the NBS chamber. The plug flow condition could represent a situation where the gas and smoke generated in A is convected to C and envelops a passenger waiting to escape from the aircraft.

In Table 4.13 are reported the 10 minute gas exposure limit and the degree of smoke obscuration; these are presented as percent involvement of panel, to the limit. (The smoke obscuration limit is assumed to be an optical density of 200, a proposed limit set by the FAA.) Values are calculated for the area to volume ratio for a wide-bodied-jet cabin. Based on these data alone it is evident that smoke, HCl, and HF were the worst offenders for the state-of-the-art materials. For the limited sampling of advanced materials and the questionable analysis, it appears that smoke remains a problem. Thus, based on these data, the development of advanced materials is not moving consistently in all the desired directions, that is, toward a reduction of both smoke and toxic gases. In fact, some of the new materials have characteristics worse than those of the old. In addition, from limited comparison it appears that although some improvements are evident in smoke reduction, and although some reduction in toxic conclusion that an improvement is feasible. Even the advanced materials' best smoke reduction (by a factor of 5) represents an increase in panel involvement in a fire from 1 to 5 percent. To prevent just one-fourth of one side of the aircraft from contributing to an unacceptable smoke level may mean that we must cut smoke levels by a factor of 10 or more, an improvement that is not evidently feasible from the data base.

Large-scale tests by NASA and FAA show that the problem of flame spread caused by small ignition sources has been reduced, an important reduction in the thermal threat, by the institution of the FAA self-extinguishing regulation. In Figure 4.3 is shown the relative damage by a mockup of pre-1968 materials, which do not conform to the regulation, and by a mockup of advanced materials. Smoke, gas and temperature levels for these two cases are shown in Figure 4.4; a reduction in the degree of involvement is shown. Unfortunately, the data does not include a comparison of some gas analyses for both the pre-1968 and new materials, such as HCl, HF, and HCN. Also it is not apparent that smoke emissions have been reduced considerably with the new materials. The only test conclusions are that the large-scale tests show a decrease in the thermal effects and a decrease in flammability and concomitant flame spread, carbon dioxide, oxygen deficiency, and carbon monoxide production.

4.5 Subgroup III - Conclusions and Recommendations

4.5.1 Post-Crash Fires

4.5.1.1 Crashworthy Fuel Systems

The primary problem lies in minimizing the effects of major fuel escape due to wing separation, tank rupture and fuel line failure. Crashworthy fuel systems, as developed for helicopters, cannot solve this problem except possibly to a very limited extent. It is recommended that consideration be given to improving the containment of fuel in fuselage and wing leading edge tanks by a crashworthy system approach together with the application of fail-safe couplings in the fuel system. Some consideration should be given to the concept of designing the main wing tanks with double walls at the root junction and near engine and landing gear pick-up points so that when wings separate or engine or landing gear breakaway in an accident fuel escape is, so far as is possible, avoided. For current designs such an approach is not feasible; the possibility of a major fire has to be considered and the survival of the occupants may need to rely on the prevention of fuselage burn-through by the use of phenolic resins, intumescent paints and similar measures. It is recommended that consideration be given to the incorporation of these features not only in aircraft currently in the course of design and to those in production but also retrospectively to those now operational. Modern low density foams and intumescent coatings may help to retard the onset

TABLE 4.12 - NBS CHAMBER SMOKE AND GAS GENERATION FOR AIRCRAFT PANELS[a]

(Flaming Exposure, Approximately 7-min Burn)

Panel number	Smoke, Dm	CO, ppm	HCl, ppm	HCN, ppm	HF, ppm	NOx, ppm	H2S, ppm	SO2, ppm
				State-of-the-art materials				
1	250	500	600	20	150	9	--	--
2	125	500	10	15	0	11	--	--
12	75	500	600	8	150	12	--	2
14	125	600	20	12	90	10	--	--
20	50	300	40	3	95	2	--	--
30	63	286	45	7	--	--	--	--
37	200	500	500	10	150	10	--	--
43	300	600	300	28	150	8	--	--
46	200	450	600	10	150	10	--	--
61	200	600	500	15	150	20	2	--
76	151	20	80	7	--	--	--	--
144	50	225	50	1	100	1	--	--
				Research and development materials				
26R	26		1	1				1
15R	217		6	7				
22R[b]	264			3				
19R[c]	43		1	1				1

[a] References 4.7.14 and 4.7.15.
[b] Does not meet FAA burn test requirements.
[c] Heavier than tentative weight limits of state-of-the-art materials.

TABLE 4.13 - LIMITING SMOKE AND GAS EFFECTS

Panel	Limiting Gases[a]	Minimum % panel involvement[b] Gas	Smoke
State-of-the-art materials			
1	HCl, HF	0.05, 0.133	2
2	NOx, HCl	2.8, 3.0	2
12	HCl, HF	0.05, 0.133	3
14	HF, HCl	0.22, 1.5	2
20	HF, HCl	0.22, 0.8	4
30	HCl, CO	0.66, 3.0	4
37	HCl, HF	0.06, 0.133	1.0
43	HCl, HF	0.1, 0.133	0.6
46	HCl, HF	0.05, 0.133	1.0
61	HCl, HF	0.06, 0.133	1.0
76	HCl, HCN[c]	0.4, 24	1.4
144	HF, HCl	0.2, 0.6	4.0
Research and development materials			
26R	HCl, SO2	30, 30	8.0
15R	HCl, HCN	5, 24	1.0
22R	HCN, (no other rept.)	56	1.4
19R	HCl, SO2	30, 30	4.0

[a] First two limiting gases reported based on 10-min Emergency Exposure Limits of the Committe on Toxicology (National Academy of Science/National Research Council) Bioastronautics Data book, NASA SP 3006, p. 474.

[b] Linear extrapolation of data, %=limit[a] 1.0/experimental concentrations (~1. % based on relative NBS/aircraft weight/volume ratios ~$1.74(10^{-5})$gm/cc/$1.9(10^{-3})$gm/cc.

[c] HCN data for lethal concentration for 10-min exposure, Ship Habitability, JPRS 65334, p. 58.

of catastrophic explosions to tanks exposed to fire; consideration should be given to the use of these materials and particularly to their efficiency in a real aircraft environment and after aging experienced during a life of many years use.

4.5.1.2 Anti-misting Fuels

Fire safe fuel research should be vigorously pursued. The potential benefits are considered to be substantial particularly because of the application to current aircraft. There may be circumstances, however, where no saving of life or property may arise but the bulk of evidence is advantageous. Problems do exist, however, with regard to the use of anti-misting additives both with regard to mixing and also degradation; until satisfactory solutions are available, AMK fuel use remains a prospect only. It's general application must depend finally on its international acceptance since it is more expensive than current fuels and will result in an increase in direct operating costs, offset only by the savings in insurance.

4.5.1.3 Inerting and Explosion Suppression Systems

In the crash situation the hazard exists mainly due to the rupture of the fuel system and application of these systems can offer little benefit in this case. Where fire breaks out but part or all of the fuel system remains intact some time advantage might be achieved by delaying the explosion. Further research into such benefits by the application of inerting by nitrogen or the use of other means of suppressing explosions could be of value in indicating the possible benefit to be gained. The main approach should be the reduction of crash fires by reducing susceptibility to system rupture and by the use of a safe fuel.

4.5.1.4 Fuselage Fire Hardening

This is primarily of concern if crashworthy fuel systems prove to be impracticable as on current aircraft and those now being developed. The purpose is to produce a survivable environment within an intact fuselage; a burn through can be retarded by surface protection using foam or intumescent paint, but close attention needs to be given to transparencies, to ensure that they can also sustain fire without failure. Work is recommended in these areas. When the fuselage is already ruptured or when doors and escape hatches are opened the products of combustion dominate the problem of survivability and a portable life support system including a smoke hood may be necessary in order to complete the escape. It is recommended that localized application of surface protective measures, in sensitive areas, and the development of transparencies to resist sustained fires be considered; the possibilities of smoke hoods should be further examined.

4.5.1.5 Emergency Escape Improvements

Aircraft escape slides have saved many lives in the past; recent experience however, shows the problem of maintaining their integrity in a fire situation. Consideration should be given to improving the protection given by slides against the effects of fire and also to the maintenance of their structural integrity.

4.5.1.6 Fire Fighting Improvements

The possibility of providing an enhanced fire fighting system from ground sources should be examined. Proposals have been made for filling the fuselage from external sources with a water fog system but this introduces other problems. A major problem is that of reduced vision due to smoke; any means of reducing this smoke would be beneficial. In addition the repositioning of emergency escape direction signs nearer the floor is recommended.

A further problem with rescue vehicles is in locating an aircraft in poor visibility e.g., Cat. III conditions. Guidance systems relying on the use of ASMI or homing equipment may be needed to enable them to operate effectively.

4.5.2 In-flight Fire Protection

4.5.2.1 Fuel Systems

The lightning strike problem has been largely overcome by the use of Jet A or Jet B (35 percent in Canada) fuel together with suitable design measures in the vicinity of the fuel vents. We must not remain complacent and improvements, where possible, should continue to be encouraged. It is recognized, however, that future aircraft incorporating composite construction may be vulnerable and it is recommended that the effects of lightning strike should be examined for such materials. Similar protection to that needed for radomes and non-metallic external tanks may be needed.

Protection of fuel systems from engine break-up will require that consideration be given to the position of the engines or that fuel systems should be armoured against impact by any likely size of engine debris. The use of nitrogen purging

or other explosion suppression to provide further inflight protection should be considered in order to enhance the integrity of the fuel system; cost-effectiveness studies of the various means of protection should be carried out.

4.5.2.2 Engine Systems

Current fire protection standards offer a satisfactorily high standard of fighting an engine fire contained within the nacelle. This no longer exists, of course, when the debris resulting from an engine break-up is not contained. Work should continue to reduce the frequency of non-containment of debris and enhance the safety of the aircraft. It is unlikely that a complete solution to the problem will be possible and the aim must be to minimize the effects, should it occur, by suitable positioning of sensitive items and, where necessary, protective measures. While progress has been made in reducing the incidence of titanium fires, effort must be continued towards their total elimination.

4.5.2.3 Crew and Passenger Compartment

The choice of interior cabin materials should primarily depend on their ability to delay the flashover and thermal effects of large inflight fires. Fires starting behind panels may be more effectively combatted by the provision of knock-out holes through which extinguishant can be discharged; consideration should be given to the possibility of compartmentalization of the space behind panels to minimize the spread of fire.

A major hazard reduction would arise if a no smoking rule were introduced and rigidly enforced. Since public opinion is unlikely yet to agree to this, major protective measures should be employed in sensitive areas such as toilet compartments; these should be provided with automatic warning and extinguishing systems. The use of rapid deployable fire curtains, to isolate parts of the cabin or service areas, should be considered.

The presence of large quantities of combustibles carried by passengers, e.g., newspapers, and liquor constitutes a serious potential fire source; it is recommended that serious consideration be given to ways of minimizing this hazard. In addition, the current policy by some airlines of using large quantities of potentially hazardous plastic products for food and drink must be questioned.

In-flight fires arise from the electrical system; short circuit protection especially in air conditioning systems, requires reassessment and the consequences of aging on the integrity of electrical systems requires review.

Efforts should be made to ensure that the flight deck will not suffer a high smoke concentration by suitable design and control of the air conditioning system. Consideration may need to be given to sealing the flight deck from the passenger cabin.

The use of the oxygen system on existing aircraft should be reviewed as a means of improving survivability in the event of toxic smoke invading the cabin. In the future the concept of smoke hoods for both crew and passengers deserves consideration both for the inflight fire and post-crash evacuation. With such devices it may be possible to incorporate improved fire-retardant materials which would otherwise result in an unacceptable toxic level in the cabin air.

Apart from the deterioration by aging of electrical systems other non-metallics - oxygen systems, seat covers and other furnishings - may similarly become less fire resistant with age. A research program to examine this situation requires to be carried out.

Where in-flight fires may be fed by the oxygen system, it is recommended that it should be possible to off-load the contents overboard. Every effort must be made to ensure that oxygen systems do not contribute to the initiation or enhancement of a fire by suitable positioning, bearing in mind the avoidance of spillage of, for example, fatty materials.

Fire extinguishers should be prominently positioned and the most suitable types should be provided to cater for a wide variety of fire types. Particularly in the vicinity of galleys, adequate protective measures must be provided.

4.5.3 Ramp Fires

These generally occur either because of faults developing in the landing gear or during refueling operations; the latter can be avoided by the use of a suitable commercially available anti-static additive. Tire and wheel failures, however, which can lead to fires fed by the hydraulic system may lead to more serious disasters even if the ground fire services are in attendance. The problems of hydraulic fluid flammability and

the reduction in tire failures are both subjects where research could usefullv be performed. Tire failures following rejected take-offs or prolonged taxiing under critical conditions, leading to the risk of landing gear fires may be reduced by providing flight deck indicators of tire pressure, a landing gear fire indicator in the flight deck might also be considered.

When aircraft are unattended consideration should be given to the provision of automatic cabin fire detection and extinction in order to avoid extensive fire damage from comparatively minor fires being permitted to continue unabated. This measure would largely eliminate this fire problem.

4.5.4 Cargo Compartments

Cargo compartment fires can arise because of the carriage of hazardous materials inadequately contained. Since no practical measures can prevent this, it is necessary to provide means of containing fires which do occur and isolating the compartment. Research is required into this problem largely, but not entirely, of an in-flight nature.

4.5.5 General Fire Precautions and Accident Avoidance

Under average conditions on the ground wide-cut fuel (JP-4 or Jet B), because of its volatility characteristics, is flammable over a wider ambient temperature range than kerosene type fuels (JP-8 or Jet A-1). The use of kerosene type fuels instead of wide-cut fuels is therefore strongly recommended from the fire safety aspect. Under certain climatic conditons e.g., northern operations, the use of wide-cut fuel, because of its excellent low temperature properties may be necessary. In addition regardless of the type fuel inclusion of a static dissipator additive to minimize electrostatic hazards during aircraft fueling is highly desirable.

4.6 Figures

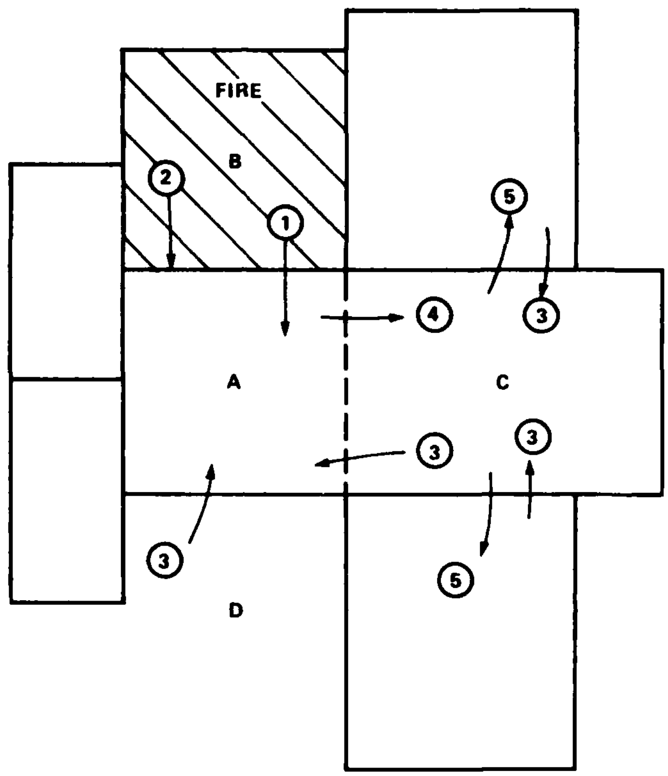


Figure 4.1 - Aircraft Environment

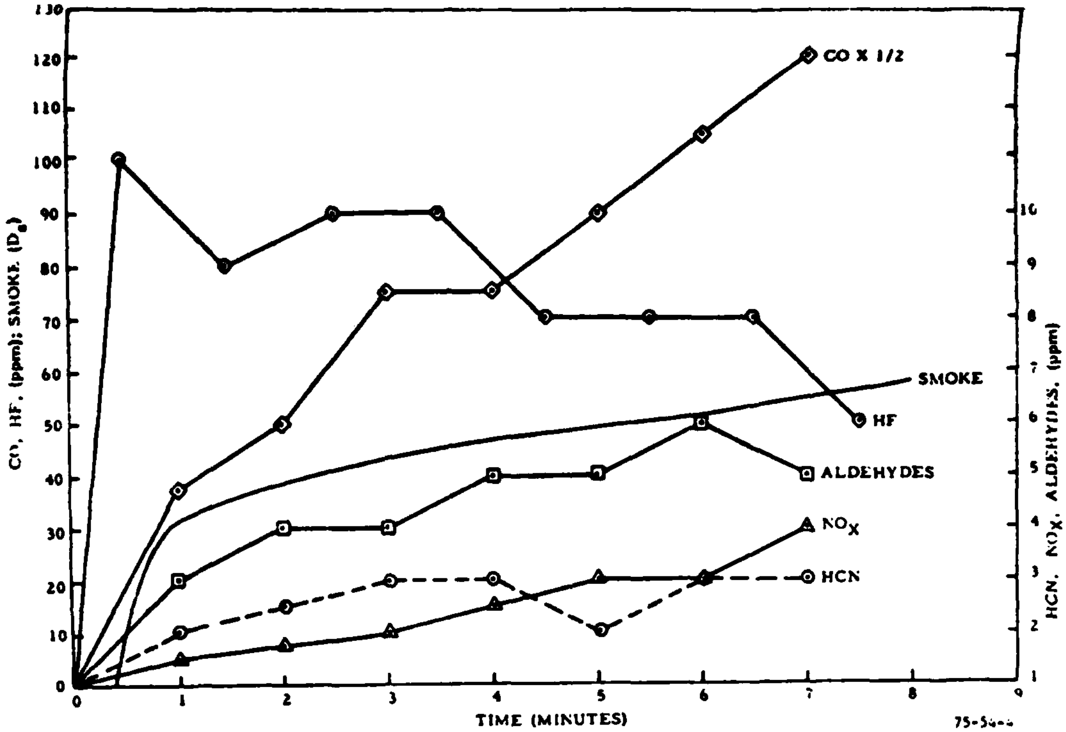
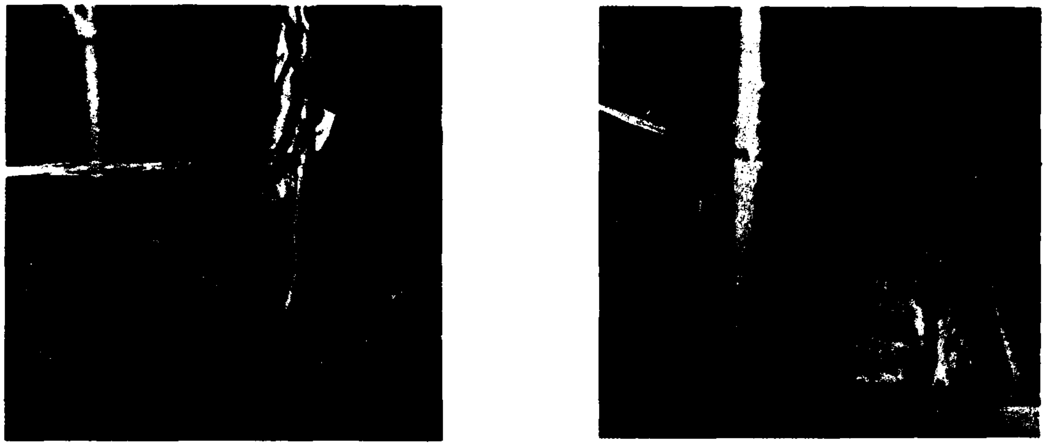
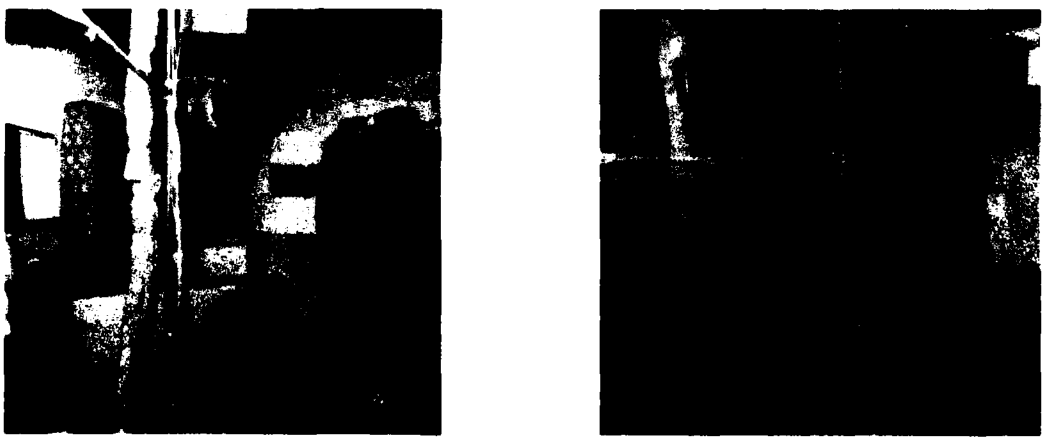


Figure 4.2 - Smoke and Toxic Gas Concentration Histories for PVF-Coated, Aramid Honeycomb Wall Panel 144 (Reference 4.7.14)



(a) Test 1: pre-1968 materials



(b) Test 2: new materials

Figure 4.3 - Relative Damages Sustained by pre-1968 Materials and Advanced Materials

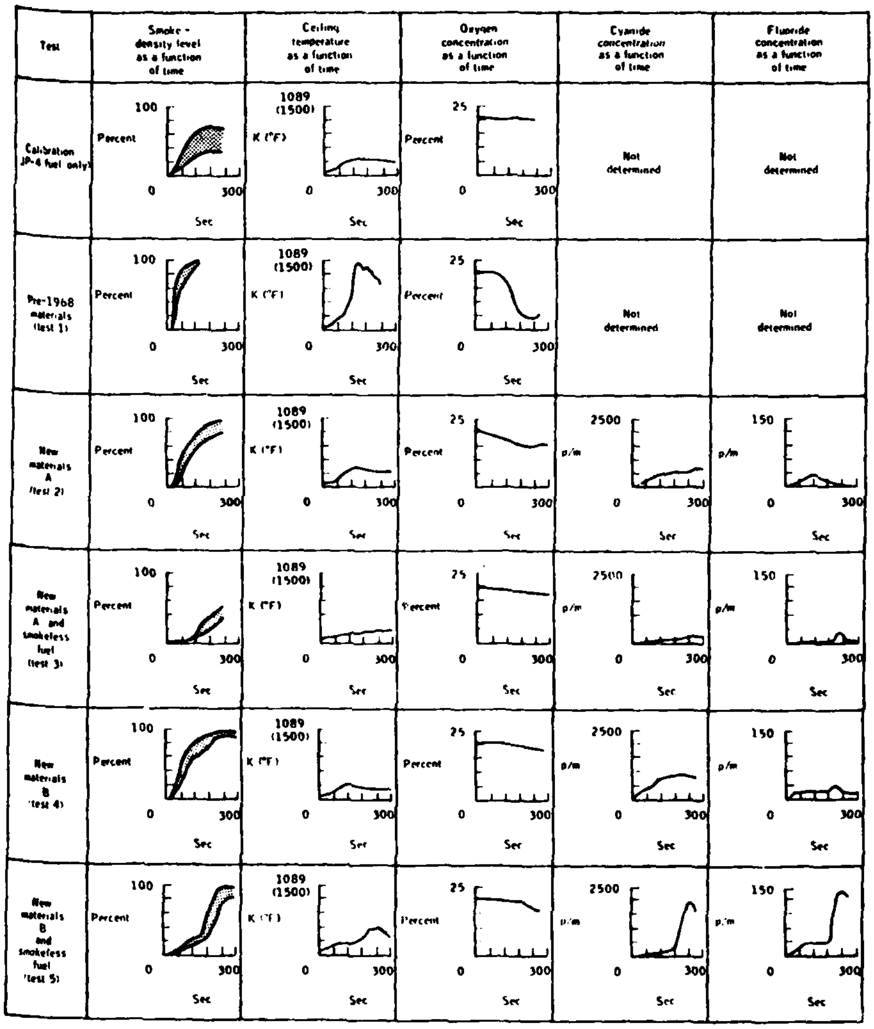


Figure 4.4 - Comparison of Selected Results of JSC Tests (Reference 4.7.16)

4.7 References

4.7.1 S. A. E. Aerospace Information Report, AIR 1537, October 1977.

4.7.2 US Air Carrier Accidents Involving Fire 1965 Through 1974 and Factors Affecting the Statistics, NTSB-AAS-77-1.

4.7.3 Fire, Fuel and Survival: A Study of Transport Accidents 1955-1974 by A. F. Taylor, AGARD-CP-166.

4.7.4 Civil Aviation Authority, British Civil Airworthiness Requirements.

4.7.5 "Crash Survival Design Guide," USAAMRDL TR 71-22, October 1971. (Revision in progress, draft to be completed by November 1978.)

4.7.6 Safety Fuel Research in the United Kingdom by R. E. Miller, AGARD-CP-166, "Aircraft Fire Safety," Paper 1.

4.7.7 Transport Category Airplane Post-Crash Fuel System, FAA Public Hearing, Contribution on AMK by R. E. Miller, pp 222-259.

4.7.8 Systems Problems Associated with the Use of Safety Fuels, R. H. Walsh, E. A. Timby and D. J. R. Robinson, AGARD Conference Aircraft Fire Safety, Rome, April 1975.

4.7.9 BAC 1-11 Low Pressure Fuel System and Component Performance Tests with an Anti-misting Fuel (FMD) at Ground Level Ambient Conditions, E. A. Timby and D. R. J. Robinson, RAE TR 77183.

4.7.10 Interim Report into Methods of Mechanically Degrading Anti-Misting Kerosenes, E. A. Timby, RAE Tech Memo EP 611.

4.7.11 "Investigation of Aircraft Fuel Tank Explosions and Nitrogen Inerting Requirements During Ground Fires," FAA-RD-75-119, Richard Hill, George Johnson, October, 1975.

4.7.12 "Integrated Aircraft Fuel Tank Fire and Explosion Protection Systems - Phase I and II," AFAPL-TR-75-93, Q. C. Malmberg, July 1975.

4.7.13 "Feasibility of Adapting a Thin Film Permeable Membrane to Jet Transport Fuel Tank Inerting System," FAA-RD-74-194, Worella Brown, et al, January 1975.

4.7.14 Sarkos, Constantine P., Measurement of Toxic Gases and Smoke from Aircraft Cabin Interior Materials Using the NBS Smoke Chamber and Colorimetric Tubes, Report FAA-RD-76-7, U.S. Department of Transportation, Federal Aviation and Administration Systems Research and Development Service, Washington DC, March 1976.

4.7.15 Gross, D. et al, Smoke and Gases Produced by Burning Interior Materials, Building Science Series 18, Building Research Division, National Bureau of Standards, Washington DC, February 1969.

4.7.16 Bricker, R. W. et al, Fire Resistant Aircraft Materials Development and Evaluation Program. NASA N76-11179, pp 833-854.

5. AIRCRAFT FIRE SAFETY - ENTIRE WORKING GROUP ASSESSMENT

5.1 Introduction

In this section the objective is to provide abbreviated summaries of the overall Aircraft Fire Safety situation by major mishap scenario and/or by specific subsystem, as appropriate. Major Working Group activity focused on turbine engine transport aircraft (civil and military) because of the greater similarity of design standards, mission profiles, better opportunity for mishap correlation and the current preponderance of this form of transportation. In many instances our fire safety related assessments are also applicable to turbine powered tactical and fighter aircraft in a non-combat threat environment. The hostile combat aircraft fire survivability has not been addressed; this matter being beyond the scope and schedule of this Working Group's activity and more appropriately could be the subject of a separate follow-on Working Group function.

Each summary will strive to include information concerning: fire safety experience as evidenced by mishap (accident/incident) data; a delineation of predominant fire hazard scenarios; the adequacy of current available technology and airworthiness standards to cope with the problem; areas of deficiency; possible approaches for correcting these deficiencies; research and development activities currently in progress applicable to the deficiency; and overall Working Group recommendations(s) concerning needed/optimal actions.

In evolving its recommendations the Working Group endeavored to distinguish between the idealistic goal of eliminating the fire threat in its entirety and the more realistic goal of emphasizing nearer-term, meaningful/acceptable payoffs which clearly reduce the fire risk while not compromising overall aircraft system safety and operational efficiency. Obviously, in progressing from the ideal to the realistic a number of potential possible solutions had to be explored; many others possibly exist that the Working Group did not even surface in its limited evaluations. In sorting through the list of possibilities, the Working Group endeavored to ask: Realistically, which truly offered engineering and economic merit for application to operational aircraft? to future aircraft? Was the proposed remedy worse than the illness? Is enough understood about the fire scenario and the elements involved to be able to suggest a best solution? or is the problem really one of focusing initially on the understanding of the fire initiation, growth and damage effects? For promising approaches what is the best implementation procedure? Should it be implemented on operational or only future aircraft? How does such a decision influence the legal vulnerability of the Airframe Company/Operator in the event their aircraft should be involved in a fire mishap related to the proposed fix in question? In essence these questions represent obstacles to be overcome and which will be overcome if a particular fire survivability enhancement technique, system, etc., truly has merit.

The legal aspects basically were not explored. Rather the study progressed on the basis that a particular aircraft design and flight safety certification complied with particular regulatory standards, enforced by appropriate authority at the time of design. Furthermore, it is recognized that these standards/regulations are adaptable and consequently will change with time. As a result aircraft built to 1950 standards cannot be expected to conform totally to 1970 standards, except in those areas considered to be critical to safety of flight. In the latter instance, compliance may be declared mandatory on a retrospective basis. Criticality to safety of flight in many instances is dictated by the consequences of lessons learned from mishaps (incidents, accidents). Today more emphasis is being placed on aircraft hazard analysis during design including subsystem failure mode and effects analysis. These too can define major areas of concern, but also are dependent on being able to predict consequences/response resulting from a particular failure and its possible cascading events. Much needs to be defined with regard to hazards assessment methodology. As our knowledge and capability improves overall system safety and fire protection engineering decisions and trade-offs will become more definitive.

5.2 Fire Hazard Ranking

An assessment of the relative severity of the various fire hazards encompassing the overall aircraft fire hazard was made on the basis of the number of occurrences and the likelihood of survival that were reflected in actual aircraft accident fire experience between 1964-1974. The fire experience data indicate that the fire hazards may be ranked in the following order of decreasing significance. Damage causes or operational conditions are also indicated for each fire hazard in order of significance.

Fire Hazard Ranking

(1) Post-crash massive fuel spill fires.

- (a) Wing/partial wing separation
- (b) Major fuel tank damage

(2) Fuel tank explosions.

- (a) Inflight
- (b) Post-crash

(3) Post-crash moderate fuel spill fires.

- (a) Minor fuel tank damage
- (b) Fuel line damage

(4) Cabin material fires.

- (a) Inflight
- (b) Post-crash

(5) Propulsion system fires.

- (a) Non-contained titanium fires
- (b) Non-contained rotor fragment initiated fires

(6) Landing gear system fires.

(a) Take-off and landing

(b) Inflight

(7) Fuel tank explosions.

(a) Maintenance

(b) Refueling

The fire hazard pertaining to fuel release from wing separation was considered to be the major fire hazard because fires resulting from this mode of fuel release occurred in about 50% of the world-wide impact-survivable fire accidents. The estimated fatalities due to fire in wing separation/fire accidents experienced by U.S. operators represented about 26% of the total U.S. survivable accident fatalities. Fuel tank explosions were ranked as the number 2 fire hazard since 8 inflight explosions were experienced, several of which resulted in non-survivable impacts, and the explosions which occurred during post-crash fires in 11 accidents impeded further evacuation. Inflight tank explosions were predominantly associated with Jet B fuels and the most recent improvements in lightning protection design appear not to have been involved. The moderate fuel spill fire hazard resulting from damaged fuel tanks and fuel lines was ranked number 3 because the fuel spill mode occurred in numerous accidents with a high percentage of fatalities caused by fire rather than impact. The number 4 fire hazard was considered to be due to cabin material fires because 3 fatal inflight fire accidents occurred but it is acknowledged that their contribution in certain post-crash fuel fire environments, largely unknown at present, could be significant. Propulsion and landing gear system fires are ranked numbers 5 and 6, respectively, and the fuel tank explosion hazard during refueling is number 7 because these fire hazards have resulted mainly in aircraft damage and losses with few fatalities. Propulsion titanium fires were considered to be more potentially serious than landing gear fires, while corrective action to preclude further refueling explosions appears to be effective for civil aircraft.

5.3 Aircraft Crash Fire Protection

Enhancement of crew and passenger fire survivability under impact-survivable crash conditions continues to represent the highest priority aviation fire safety need. Specific typical fire scenarios along with specific world-wide civil turbine aircraft accident experience for the period 1964-1974 were provided in Section 2 of this report. The crash fire scenarios are varied but generally entail the dynamic spillage of fuel, for example due to the separation, penetration or rupture of a fuel tank, coincident with ignition by either direct fuel ingestion into the engine, or by hot surface, mechanical or electrical sources, followed by rapid fire propagation and envelopment of aircraft structure. External fire effects in time can induce further rapid degradation of passenger survivability by inducement of fuel tank explosions; heating of fuselage skin with resultant involvement of interior cabin materials as exhibited by smoke and toxic gas generation and initiation of internal combustible material fires; and direct penetration by smoke and toxic hot gases via burn-through of the fuselage. The overall situation is further complicated by the fact that no two impact survivable crashes are the same with regard to fuel release mode, fuselage structural-integrity subsystem response, and fire initiation, propagation and damage effects versus amount of time available for passenger survival. Depending on the specific conditions, available fire survival time can vary from 40-60 seconds to several minutes. Obviously, a number of approaches for enhancement of fire survivability can be postulated. Acceptance of any approach must be supported by clear-cut engineering studies which show that overall aircraft system safety and performance is not compromised by attempts to significantly improve crash-fire survivability. Concurrently the overall safety benefits must also be complemented by acceptable life-cycle-cost analysis which indicates continued, economically feasible flight operations. The safety advantages versus cost must be "acceptable" in the case of civil transports to the paying public. Because of the economic considerations, it also becomes immediately apparent that implementation of additional fire survivability measures must be pursued on a world-wide basis, through appropriate civil aviation airworthiness authorities. What are the approaches to enhancement of crew and passenger survival from fire in an impact crash environment?

5.3.1 Fuel System Protection - A review of world-wide civil turbine aircraft accident experience for the period from 1964-1974 indicates that:

- 97 impact-survivable accidents occurred which resulted in spillage of fuel and post-crash fires.
- Wing - separation occurred in 48 (49%) of these accidents.
- Fuel tank explosions occurred in 11 of these accidents due to flame penetration through tank vents or external heating from burning spilled fuel.

It is very apparent that a significant enhancement of passenger survivability should be possible by reducing the vulnerability of the fuel system to impact induced fire and explosions. The options available include minimization of fuel leakage, utilization of a more fire resistant fuel, and incorporation of on-board fire and explosion suppression systems capable of performing effectively under impact survivable aircraft crash conditions. These options obviously are not new. The Working Group in assessing the options concentrated on reviewing the state-of-the-art, the status of current research and development activities, and the prospects from a technology viewpoint of their eventual practical application to fixed wing aircraft. Each of the options is discussed below.

5.3.1.1 Crashworthy Fuel System

In an impact survivable aircraft crash the greatest nemesis is the occurrence of external fire due to uncontained fuel. Even with the rapid response of fire fighting and rescue equipment and crews, the chances of survival are significantly reduced. If a person experiences the crash phase without immobilizing injuries, often the external fire rapidly closes any escape opportunity by creating an environment which exceeds an individual's physical limitations, eventually rendering him incapacitated. The environmental degradation manifests itself in the generation of toxic gases, high temperature, and smoke (visibility degradation). Although in some crash occurrences the fuselage may remain intact and serve as a protective shield from any external fire, the effect is only very temporary. In a very short time span the protective shield becomes heated resulting in the degradation of interior fuselage materials and their eventual ignition, in other areas, subjected to intense direct flame impingement, localized burn-throughs occur providing a direct path for vitiated air and flame to ingress the habitable areas. The heating and flame penetration effects will vary with the aircraft design and materials utilized as will the toxic gases generated. Although man's physical limitations to temperature and selected toxic gases such as carbon monoxide are well quantified, meaningful response data to the combined temperature and varied multicomponent vitiated atmosphere conditions present in post-crash fire environment are not available. All that can be concluded is that the available escape time under such conditions is very limited, in many instances less than a minute.

The direct solution is to provide an aircraft fuel system that is crashworthy, at least under the impact force conditions which human beings could be expected to survive, and thereby prevent significant fuel leakage from occurring. Crashworthy fuel tanks have been successfully applied by the U.S. Army to their helicopters resulting in essentially total elimination of post-crash fire fatalities under survivable conditions. Prior to incorporation of a crashworthy fuel system, post-crash fire was the principal cause of helicopter accident fatalities. The U.S. Army's progress and solution deservedly must be treated as one of the major, if not the most significant, aerospace fire safety accomplishments of the past twenty years. Pertinent information on the U.S. Army's design approach is documented in USAAMRDL Technical Report 71-22, Crash Survival Design Guide, revised October 1971. It is understood another revision is currently in progress. Those interested should refer to the above document for detailed design information.

What does the Crashworthy Fuel Tank System consist of and how applicable is it to fixed wing aircraft?

The helicopter crashworthy fuel system essentially is comprised of tanks that will deform with the impact but not rupture and breakaway self sealing valves. The tanks and fittings weigh more than conventional aluminum systems resulting in an approximately 3% average increase in aircraft weight.

Installation of crashworthy fuel cells in a large fixed wing aircraft with its inherent internal structural complexity will result in a greater than 3% increase in aircraft empty weight, probably closer to 6%. In addition to the weight penalty, installation of such cells in the complex wing structure of existing large fixed wing aircraft will result in a loss in fuel capacity. The fuel loss can be significant, for example in a recent USAF study conducted for installing standard bladder cells into the center wing of a cargo/transport aircraft, a volume loss in excess of 20% of the original fuel volume was determined. Aside from these significant weight and range penalties, the initial cost of installation and the attendant recurring operational costs would also be very high. True weight, range and cost penalties can be more precisely quantified only after developmental effort is conducted to validate the effectiveness of the installed system on large transport type aircraft.

It would appear based upon the associated penalties that incorporation of total crashworthy fuel system on large transport aircraft will not occur unless directed by the agreement of world-wide aviation airworthiness authorities. Even then the application appears most logical to new aircraft designs where minimization of penalties can be assessed during the engineering phase.

With respect to current operational aircraft, serious consideration should be given to a selective partial application of the crashworthy fuel system approach for enhancement of crew and passenger survival. Certainly, all fuel tanks proximate to passenger areas would be prime candidates, these include any internal fuselage tanks and immediately adjacent wing integral tanks. Additionally, an in-depth analysis of impact survivable mishaps involving wing separation should be conducted from the viewpoint of identifying low penalty, potentially high payoff design approaches for enhancement of fuel containment capability. Typical approaches for example could include compartmentalization of wet wing tanks, better isolation of tanks from wing root separation point via a double wall, and incorporation of breakaway fuel lines with self sealing valves.

To our knowledge no significant research and development activity is being pursued anywhere in the world with respect to crashworthy fuel tanks for fixed wing transport aircraft. It would appear based upon the success achieved with helicopters that a "fresh look" with associated engineering development and test activities is needed which addresses both the partial and total future aircraft system applications. If significant, near-term, positive protection against the post-crash fire threat is really desired, enhancement of fuel containment capability under survivable impact conditions cannot in our estimation be ignored. In addition to the principal payoff, more effective ground fire fighting/rescue operations because of the gradual, if any, fire buildup after impact, and less concern for the involvement of interior cabin materials with their debilitating toxic and smoke product effects on human escape, could result.

5.3.1.2 Anti-misting Kerosene

Presently, several turbine fuels are in use for civil and/or military aviation operations. These fuels are all of the hydrocarbon type and differ primarily with respect to volatility which manifests itself in the flash point temperature, vapor pressure and distillation characteristics of the particular fuel. With respect to conventional jet fuels, in the interest of simplification, only two widely used fuels were considered by the Working Group. The first is a wide-cut type desinated as NATO F-40, ASTM D 1655 Jet B and U.S. Air Force JP-4; the second is a kerosene designated as NATO F-34, ASTM D 1655 Jet A and Jet A-1, and U.S. Air Force JP-8. The wide-cut fuels are inherently more volatile as exhibited by their flash point temperature, typically less than -18°C (0°F) compared to 38°C min (100°F min) for the Jet A type. Because of its higher volatility the Jet B fuel is potentially more vulnerable to ignition and rapid flame propagation under impact survivable aircraft conditions. The magnitude the real world difference between Jet A and Jet B types with respect to fire vulnerability is difficult to quantify because of the effects of crash dynamics on fuel dispersion. The latter in many instances results in the release of fuel in a manner which generates heterogeneous liquid fuel mist-air mixtures which exhibit flame propagation and consequent flame intensification behavior similar to the more volatile Jet B fuels for which such mixture formation is not needed for rapid fire buildup. Several in-depth analyses of major aircraft crash mishaps have been conducted, most notably by A. F. Taylor, Cranfield Institute of Technology and the Coordinating Research Council Inc., in an attempt to distinguish the effect of fuel type on fire fatalities in otherwise survivable crash conditions. Although no two mishaps are exactly the same, these recent analyses indicate a small, but nevertheless positive safety advantage for the Jet A fuel. Equally important, however, in the estimation of the Working Group is the fact that both types of conventional fuels still exhibit a serious post-crash fire threat to the survivability of crew and passengers.

In certain countries the Jet B fuel has been relegated to emergency use with the Jet A type specified for everyday normal operation for safety reasons. A gradual transition to a Jet A fuel for world-wide operations appears underway, however, the need will continue to exist for the lower viscosity, more volatile Jet B where low temperature conditions so dictate. The extent of a transition to a Jet A fuel will be affected by fuel availability not only for aircraft operations but also for other industrial, domestic, etc., uses. The outlook and considerations requiring attention regarding fuels, particularly for aviation, have been assessed in AGARD Advisory Report Number 93 on Future Fuels for Aviation. The near-term (year 1990-2000) problem stems from an increasing demand for the mid-distillate fraction from crude oil in parallel with greater dependence on alternative fuel sources such as from heavy crudes, shale, tar and coal liquids. While the producton of additional mid-distillate is quite feasible, special processing would be required to produce the needed quantities of low-freezing-point, low aromatic jet fuel called for by current specifications. Consequently, considerable effort is being pursued toward the re-examination of the optimum fuel specification-aircraft system combination. This approach is focusing on the development of a data base which will allow optimization of future fuel characteristics taking energy efficiency of manufacture and the trade-off in aircraft and engine design and performance into account. The present indicators with respect to future aviation fuels foretell of a fuel more like the Jet A type but with possible higher allowable aromatic content and higher freeze point with preservation of flash-point in the vicinity of 38°C (100°F)

With regard to fire safety no significant change in potential vulnerability is anticipated, however the fire characteristics of candidate alternate jet fuels will require definition in conjunction with the production, utilization trade-offs previously mentioned. In summary, current jet fuels offer a high fire threat in post-crash environment; future conventional hydrocarbon fuels will exhibit a similar fire vulnerability. It is also quite apparent that jet fuel specification changes will occur and consequently any fuel modifications via additives for the purpose of reducing the fire vulnerability under dynamic crash conditions must continuously be aware of these possible changes in order to maximize the potential long-term acceptability of any fire safe fuel formulation(s) proposed.

During the past 15 years considerable research and development has been performed in the United States and United Kingdom toward the formulation of a modified fuel for aircraft applications to reduce the post-crash fire hazard. The overall effort has been motivated to a large extent by the desire to reduce aircraft post-crash fire vulnerability and for military applications the additional desire to enhance aircraft survivability in a combat (gunfire) environment. Specific approaches have included: gellation and emulsification of Jet B and Jet A type fuels; incorporation of halogenated flame inhibiting additives in Jet A and B fuels; and more recently alteration of the misting properties of Jet A fuel under dynamic loading conditions. These earlier activities have shown that any practical fire safe fuel concept must from the start have a low volatility fuel as the base fluid and furthermore must not drastically alter the compatibility, fluidity and low temperature performance characteristics associated with normal aircraft fuel system and engine operating requirements. Of the approaches investigated to date, the anti-misting additive approach comes the closest to meeting the above requirements. This approach was initially conceived in about 1967 and is being pursued in a cooperative manner by the United Kingdom and the United States. At present the bulk of modified fuel testing activity is being conducted with FM-9 produced by Imperial Chemicals Industries, Limited. Concentration requirements for start of effective performance is 0.3% by weight proportions in Jet A fuel. Reduction of the degree of atomization has two fire safety advantages in crash environment, first a reduction in the probability of ignition upon exposure to transient ignition sources such as friction and electrical sparks, and secondly, in the event of localized ignition reduction in the likelihood of flame propagation throughout the fuel-air mixture. Obviously where the antimist fuel is subject to longer-term exposure to an ignition source, for example impingement on a hot engine case, its probability of ignition should be comparable to the neat fuel. However, in a dynamic crash environment should ignition of the latter type occur, propagation through the remaining suspended atomized fuel-air mixture would probably still be defeated and a small localized fire would result. In essence then, the antimist fuel offers its potential safety advantages during the critical dynamic impact and deceleration phases of a survivable aircraft crash by preventing the formation of a widespread fire ball which would ignite any major fuel spillage in the vicinity thereby producing a long lasting and destructive ground fire which would nullify many passenger egress opportunities. The antimisting fuel therefore has a safety payoff during a small but critical phase of the survivable crash fire scenario which offers excellent prospects for negating the entire, more typical post-crash scenario. Recognizing the hopefully low frequency with which an antimisting fuel will be required "to do its thing;" high confidence must be demonstrated in the standby effectivity of such a fuel. The achievement of the required level of effectivity must then be weighed against other flight safety degradation effects; subsystem engineering changes; worldwide availability of such a fuel; and overall implementation costs.

It is the opinion of the Working Group that the antimist fire safe fuel approach offers high potential payoff for enhancement of passenger/crew escape under the survivable impact fire scenario. Unfortunately, unless the relatively low level of research, development and aircraft subsystem testing can be very significantly increased the likelihood of an antimisting fire safety fuel attaining operational usage in current aircraft is not considered high. It is understood that a joint United States/United Kingdom agreement has recently been established to expedite research and development effort on anti-misting fuel to provide a comprehensive engineering basis by mid 1980 for decision whether to proceed further with this approach for actual aircraft application.

In this regard, the current future jet fuel uncertainty can also provide an excellent opportunity to transition an anti-misting fuel into future operational use. In view of the fact that in-depth programs are being pursued or planned to look at engine and fuel system modifications required for reliable, effective employment of a jet fuel with potentially higher freeze point and higher aromatic content, the additional complications associated with incorporation of an antimisting additive should be amenable to assessment as an integral part of the overall future jet fuel program. This opportunity should not be overlooked. It is imperative that AGARD in conjunction with the other military and civil aviation authorities provide immediate impetus in this area. Near-term effort should place emphasis on the overall effectivity of FM-9 additive with a representative worse case fuel of the future, for example the reference fuel that will be utilized for investigation and development of propulsion and fuel subsystems. Additive refinements should be pursued as necessary to assure compatibility and effectivity for reduction of survivable impact crash environment fire vulnerability. Optimum degradation techniques for reliable and efficient utilization and projected future propulsion systems should be defined and included in the overall engine development and test programs. When appropriate, the impact on and potential engineering solutions for the design of an aircraft fuel system capable of reliably utilizing a

fire safety fuel should also be aggressively pursued. In this manner, an anti-misting fuel can be used in an aircraft which has been optimumly designed, ground tested and flight tested for its specific employment.

5.3.1.3 Fuel Tank Inerting/Explosion Protection Systems

Several active and passive fire and explosion protection systems for fuel tanks are presently in use for many military and very limited civil aircraft applications. In the case of the military applications the incentive is primarily the enhancement of in-flight combat survivability. The civil application is principally limited to wing tip vent inlet and surge tank protection against ingress of flame triggered for example by external lightning strikes. The fuel tank fire and explosion protection techniques which are currently considered to be state-of-the-art include: (1) inerting of the ullage via the introduction of nitrogen gas from a liquid nitrogen (LN_2) source, (2) packing of the fuel tank with reticulated polyester-polyurethane foam and, (3) the combination of a flame radiation sensor with a halogenated hydrocarbon fire extinguishant for automatic early and rapid suppression of any internal combustion process. With respect to transport aircraft. The LN_2 inerting system is presently only installed on U.S. Air Force C5A aircraft, where, in addition to inerting, additional LN_2 is carried on-board for combatting in-flight fires in non-habitable external dry bays such as wheel bays. Reticulated polyester polyurethane foams again find utilization primarily in military aircraft of the tactical, close-support and medium transport types although they are used in certain agricultural aircraft. The chemical agent explosion suppression system at present is employed on selected civil transport aircraft and limited only to vent/surge tank protection. It is rather apparent that the decision to incorporate any of these protection techniques has predominantly been driven by in-flight survivability consideration. The potential for these protection systems alone to significantly reduce the vulnerability of an aircraft to the crash, impact induced external fire threat is inherently low. These explosion protection techniques require intact, confined volume conditions for high effectivity; consequently, whenever the boundaries of the fuel system are drastically altered with the resultant external release of fuel, such as in the crash situation, no protection is afforded against ignition of the released fuel by external sources. Where some of the fuel tanks remain intact in the crash environment, these techniques can provide some degree of protection against secondary catastrophic fuel tank explosions induced by the external fuel ground fire condition. The latter, as exhibited in several prior actual aircraft survivable impact scenarios, could contribute to an extension of available time for passenger/crew egress, by slowing down the total fire/explosion buildup phase. Coincident with this direct potential benefit, is the closely associated extension of the time envelope for realizing fire extinguishment and control actions on the part of ground fire fighting and rescue operations.

Realization of these potential benefits requires a total fuel system protection scheme. The best available alternatives are inerting with nitrogen and utilization of explosion suppression reticulated foam materials. The inerting approach currently requires the storage of LN_2 on-board the aircraft and a suitably controlled distribution system that assures adequate dilution of tank ullage oxygen content throughout the entire aircraft operational profile. This imposes a direct weight penalty to the aircraft, initial system installation costs, ground facilities for storage and transfer of LN_2 for aircraft system replacement at the various airports/bases throughout the world, and recurring costs for LN_2, ground servicing, and subsystem maintenance. The cost, weight penalties associated with LN_2 for airline applications was addressed by the AIA at the Spring 1977 FAA Hearings on Fuel Tank Protection, in Washington D.C.

The reticulated polyurethane foams have not been evaluated with regard to effectiveness in an externally heated fuel tank environment associated with aircraft crash fire scenario. It is known that these type of materials are susceptible to thermal degradation, pyrolysis and eventual spontaneous ignition as temperatures progress from 93°C (200°F) on above 232°C (450°F). As a result, their durability and flame suppression performance under initially elevated environmental temperature conditions must be suspect. Aside from the questionable performance of crash environment, these materials impose an approximately 5 volume percent fuel penalty due to displacement and fuel retention considerations. The latter translates into and approximately 0.3 lbs/gal recurring fuel system operational weight penalty.

The chemical suprressant explosion protection system like inerting with nitrogen offers similar potential benefit in crash environment condition providing that adequate assurance of agent dispersion exists. The latter requires continued availability of electrical power to enable sensing of any internal combustion process induced by external fire effects and for the triggering of timely agent dispersal. In addition the system must be capable of effective operation at elevated temperature (due to external heating effects). These requirements impose additional complexities. Testing of the chemical suppressant protection system in a simulated crash fire environment has not yet been conducted.

Research and development activities are currently underway to provide improved fuel tank explosion protection systems. Approaches include: (1) development of on-board inert gas generator systems for tank inerting as alternatives to use of LN_2, (2) reticulated polyether polyurethane foams offering much improved hydrolytic stability and thereby offering a marked improvement in field life, and (3) a melded nylon (polyamide)

fibrous flame suppressor developed in the United Kingdom which combines lightweight 8.5 g/l (0.53 lb/ft^3) with excellent chemical stability, and (4) metal foil tank filler materials which offer combustion overpressure attentuation with prospects of much better higher temperature durability compared to plastic foams. While these development activities offer the potential for improvements in logistic, maintenance and associated reduction in operating costs when compared to the state-of-the-art techniques, weight penalties are still significant and payoff in the survivable crash environment has not been validated.

5.3.2 Aircraft Fuselage Fire Hardening

In parallel with efforts to provide better fuel containment, fire safe fuels, and improved fuel tank fire and explosion suppression capabilities, considerable research and engineering evaluations have been conducted on hardening of fuselage sections to external fire as well as the development of interior cabin materials which are inherently more compatible with the intent of enhancing passenger survivability in an external fire environment. We have noted earlier, that the time available for human survival in a survivable crash involving external fire is very short due to the intolerable heat, toxic gas and smoke and environment conditions which are rapidly generated. Obviously, the preferred solution is the minimization of fuel fed external fire occurrence. As we have seen there is no near-term simple, totally acceptable or validated solution in either the fuel or fuel tank areas which could be reasonably implemented on current fixed wing aircraft. It should be inherently apparent that approaches proposed for current aircraft fire hardening where the apparent benefits are even more questionable, face similar acceptance/implementation problems. Nevertheless, the aircraft fuselage fire hardening area in recent years has received the greatest world-wide research and development emphasis. Much of the emphasis stems from in-flight interior cabin fire mishaps which resulted in high passenger mortality due to toxic products and heat effects. The in-flight fire scenario per se will be addressed in more depth in a later section. The response of the interior cabin to external fire such as in a crash mishap, similar to in-flight, can also seriously aggravate the opportunity for passenger survival. The advantages to be gained in a crash fire environment, however are much more difficult to assess particularly if the fuselage does not remain intact or once egress doors have been opened.

Probably the best example of what is possible in the area of aircraft fuselage fire hardening is depicted by tests conducted in the United States by NASA utilizing the airframe of a C-47. The fuselage was divided into two sections. One section was protected with a semi-rigid closed-cell polyisocyanurate foam at a density of 30-60 kg/m^3 which was applied internally against the skin of the aircraft. The other section was of standard aircraft construction. The entire fuselage was subjected to 18,500 liter JP-4 pool fire environment. The test fire lasted approximately 13 minutes. The standard section essentially melted away, while the protected section was charred but still intact. More importantly the cabin interior temperature for the unprotected section reached approximately 250°C in less than 2 minutes, whereas the protected section exhibited no change in cabin interior air temperature for up to 6 minutes, with little or no smoke or gas evolved in the interior. Assuming an aircraft is engulfed in external fire, the benefit of such fire hardening is realizable only if ground fire fighting and rescue are in a position to respond rapidly and effect significant fire extinguishment action. Fire hardening of the fuselage extends the survival time envelope available.

Although significant progress has and is being made with regard to fuselage fire hardening materials, their application to current operational aircraft does not appear to be practical from cost and weight penalties versus benefits to be gained viewpoint. Research and development activities should be continued primarily with the objective of integrating advanced fire hardening approaches into future aircraft design. It is the opinion of this Working Group that for these materials to have significant payoff they must be utilized in aircraft designed to be more crash resistant, i.e. provide for greater probability of fuselage remaining intact under survivable impact conditions. In this regard, additional high realism fuselage external pool fire exposure tests are required to definitize extent and rapidity of internal environment degradation as influenced by crash induced fuselage openings as well as normal escape openings (emergency doors and windows, etc.). Tests should be conducted with standard fuselage/interior material configurations including representative carry-on combustible material fuel loading (e.g. newspapers, magazines, coats, etc.). The baseline tests should then be complemented, based upon information acquired, by appropriate enhanced passenger fire survivability material/design approaches.

In recent years intumescent paints and phenolic coatings have been developed through NASA Ames Research Institute/Industry efforts which if judiciously applied to external fuselage and fuel tank structure can provide hardening against heat and flame penetration into critical areas. Additionally transparent material technology for window applications is available which permits structural integrity and fire resistance under crash fire scenario environment conditions. Engineering assessment of the application of above approaches for current and future aircraft should be pursued immediately.

5.3.3 Improved Emergency Protection of Crew/Passengers

Enhancement of human escape opportunities under impact survivable aircraft fire environment conditions have thus far been addressed from the viewpoint of protection system and fire hardening techniques requiring major modification and penalties for near-term implementation. Realistically, then, little hope can be placed on their effecting any improvement in the aircraft post-crash fire survivability scenario for at least twenty years. Any near-term improvements will therefore have to be based upon the enhancement of human survival under the essentially unabated external fire environment condition. This means counteracting a fire scenario involving rapid fire propagation as a result of spilled jet fuel and aggravated by a fuselage/interior materials combination which is vulnerable to burn through and prone to the rapid generation of an internal atmosphere which is incompatible with favorable human response and sustenance of life. In the survivable impact crash fire scenario the threats to human beings in order of importance are inhalation of hot, toxic gas; direct, initially localized, exposure to fire; visibility degrading smoke; flash-over within interior fuselage area due to accumulated combustible pyrolysis products; and the possibility of sudden eruption of jet fuel flame front due to explosion of adjacent fuel tanks. It is the opinion of this Working Group that the most direct way to expand the available escape window is to provide for each individual a portable life support hood with independent air supply which could be donned in advance if a potential mishap situation is known to exist, or with proper education of purpose, could be rapidly utilized in the event of an unexpected mishap. The hood obviously needs to be lightweight, stowable, fireproof, provide adequate visibility, and easy to use. Individual life support hood system design should also provide protection necessary for survivability enhancement resulting from in-flight conditions due to sudden decompression as well as interior cabin fire occurrences. A multifunction hood design would require that it be disconnectable from aircraft emergency oxygen system, and upon disconnect for egress purposes provide a portable 3-5 minute air supply reservoir or source. A comprehensive discussion of this matter is provided in AGARDograph No. 221 on Advanced Techniques in Crash Impact Protection and Emergency Egress from Air Transport Aircraft by R. G. Snyder.

Another area which warrants attention as a possible near-term approach for enhancing human fire survivability relates to ground fire fighting and rescue operations. Major emphasis in these operations is external application of fire fighting agents for extinguishment of fuel fire and cooling of fuselage structure. Although these actions are essential, the Working Group also suggests that equal emphasis in attention is required toward preserving from without the internal environment of habitable fuselage areas. One approach for example might entail the deployment of "life lines" to the fire engulfed fuselage. These "life lines" could be mechanically launched with sufficient force to penetrate the aircraft structure and then transmit water so as to exit as a finely atomized fog to provide cooling of the interior atmosphere, prevention of solid combustible degradation and fire involvement, washing action for smoke/toxic products generated, and direct thermal protection of personnel. The life lines must be fireproof and possess appropriate strength characteristics under high temperature conditions. Materials technology advancements in recent years suggest such an approach may indeed be feasible. Further engineering and physiological analysis appears appropriate.

Finally, emergency egress from aircraft in many instances is dependent upon emergency escape chutes which must be capable of withstanding not only direct flame but also the radiation and hot gas environment from nearby massive fires. Recent large transport aircraft mishaps have shown definite weaknesses in this respect. A reassessment of performance specification requirements under fire environment conditions needs to be pursued and appropriate upgrading actions executed on a high priority basis.

5.4 Inflight Fire Protection

Aircraft inflight fire problems are generally associated with either the failure of power generation and/or distribution system thereby providing an ignition source to proximate combustible materials, or the failure/leakage of combustible fluid reservoirs and lines in the vicinity of existing sources of ignition, or the generation of an ignition threat in highly hazardous areas of the airframe by an external source for example a lightning strike, or finally by the careless action on the part of people such as disposing of lighted cigarettes in lavatory areas. Fire while inflight has and always will be viewed as an undesirable and potentially catastrophic event. As a consequence of such an attitude aircraft design has placed greater and greater emphasis on the basic prevention of fire complemented by appropriate protection measures such as containment, detection and extinguishment and control. Additional measures are continually integrated based on the "lessons learned". Overall the excellent inflight fire experience record of the past 11 years exhibits directly the payoff reaped from prior fire protection engineering activities. Although numerous inflight incidents occur, because of the prevention and control measures utilized, the great majority lead to benign effects. As implied above and discussed in Section 2 a few major inflight fire mishaps are still being experienced principally with respect to propulsion installations, fuel system, and interior cabin areas. Specific areas of major concern will be discussed; where applicable protection measures were previously addressed, pertinent descriptive and penalty information will not be repeated.

5.4.1 Propulsion Installation

Propulsion installations and other power generation equipment such as auxiliary power units which are utilized in civilian and military aircraft have always been recognized as inherently providing a high fire threat potential. The fire threat exists because of the location of various flammable and combustible fluids proximate to various sources of ignition e.g., hot engine surfaces. Accordingly, it is not surprising that considerable fire protection engineering attention is provided to the safe integration of such equipment on-board aircraft. The fire protection approach utilized embodies fire prevention, fire containment and isolation, and detection and extinguishing capabilities as necessary. A number of fire scenarios are possible and have been discussed in some detail in Sections 2 and 4 of this report. On the basis of the mishap analysis performed by Subgroup I, the propulsion installation fire scenarios have not been major contributors in recent fire related, fatal transport aircraft accidents. This experience indicates that current fire protection engineering criteria and measures, particularly for the intact engine and nacelle scenario, are adequate. Although improvements in fire detection reliability, particularly from the viewpoint of reducing false warning problems and speed of response, and in effectivity of fire extinguishing agents are desirable, these are not viewed as being pressing safety of flight problems. In reviewing the propulsion installation problems, it is quite apparent that continued strong attention must be provided to the potential vulnerability of aircraft to fires induced by uncontained engine failures and internal engine metal fires. With respect to the uncontained engine failure current engine design practices as well as careful engine/airframe integration techniques must continue to be stressed to minimize non-containment events and in the event of actual occurrence to preclude interaction with critical areas of the aircraft, i.e. fuel tanks, hydraulic lines, habitable areas.

With regard to the metal fire problem, this has largely been encountered with titanium, although other metals such as magnesium also pose fire problems.

Titanium has been used in the compressors of turbine engines for over 20 years because of its high strength-to-weight ratio (56% weight-of-steel), high melting temperature (1950°K) and excellent corrosion resistance. While these are significant benefits, titanium also has a disadvantage in that its spontaneous ignition temperature (1600°K) is below its melting temperature. When a titanium blade is heated by rubbing, aerodynamic heating, or as a result of a blade fracture, it will ignite before it melts and sustain burning until pressure and air velocity conditions are reduced below the necessary range or until the titanium is consumed.

Titanium fires are fast burning, i.e. 20 seconds or less, and are extremely intense. The molten particles in titanium fires generate highly erosive hot sprays which have burned through compressor casings with resulting radial expulsion of molten or incandescent metal. This could lead to a secondary fire in the engine compartment as a result of damage to fuel and oil lines.

Engines with titanium rotors, stators, and casings have experienced titanium fires since the mid-1950's during ground tests and inflight. Damage from these fires has ranged from contained blade burning to 360° penetration of the casing and penetration of external flammable fluid lines. The fires have been generally caused by titanium rubbing on titanium primarily as a result of compressor blade, disk, and rim failures and blade tip rubs with the casing. While titanium engine fires have resulted in substantial engine and compartment damage, there is no record of a fatal accident being caused by a titanium fire in civil air carrier operations.

The current FAA requirement is objective in nature relative to the titanium engine fire problem and states that: "The design and construction of the engine and the materials used must minimize the probability of the occurrence and spread of fire because of structural failure, overheating, or other causes." The FAA is supporting an effort by the National Bureau of Standards to develop titanium usage guidance material for assistance in evaluating compliance of engine designs with the current requirement. The CAA has adopted new requirements and recommendations contained in Blue Paper Number 678, dated 21 October 1977, which indicates that an engine design will be assumed to be vulnerable to titanium fires if stationary titanium material exists in areas where:

(a) pressure will exceed 2 atmospheres (i.e. 200 KN/m^2)

(b) relative air velocities are in excess of 50 m/sec,

(c) the geometry is such that relatively thin titanium sections exist which can be rubbed, directly or after shedding, by rotating parts.

CAA Paper Number 678 also suggests that engine designs may minimize potentially dangerous rubs by:

(a) large interblade row clearances,

(b) not using titanium for adjacent rotating and static parts,

(c) attention to spool movements under transient and bearing failure conditions,

(d) shrouding stators to avoid trapping debris under blade tips, and

(e) ensuring that any titanium features at the front of the engine, e.g. entry guide vanes, are robust and unlikely to shed thin, easily ignited sections.

CAA Paper Number 678 further specifies if the possibility of a titanium fire cannot be ruled out that an engine approval will be qualified to limit its use in aircraft where such fires are unlikely to be hazardous. This policy is reflected in CAA Engine Type Certificate Data Sheet Number 4001 for the Olympus 593 Mark 610-14-28 engine installed in the Concorde which contains the requirement: "In view of the extensive use of titanium, particularly for the compressor stator blades, external provision must be made against the outbreak of a titanium fire in installations where this might create a major hazard." Since the Olympus 593 design incorporates titanium LP and HP compressor blades and stators and intermediate casings, the Concorde provides a titanium fire barrier bonded to the underwing firewall over the intermediate, HP, and delivery casings. This protection will withstand penetration by the type of titanium fire produced by a titanium fire test rig which was based on analysis of past titanium fire incidents.

A U.S. manufacturer of engines which have experienced titanium fires in service is engaged in a titanium fire control program to provide fire barrier protection for external fuel and oil lines on a short range basis and to develop design features on a long range basis for fire containment within the casing. NASA and the USAF are also sponsoring contractual, university grant, and in-house research programs to allow titanium to be used in engines such that only unsustained combustion would occur under abnormal operating conditions. These programs pertain to titanium combustion fundamentals, rub energetics, blade coatings, and new alloys and are scheduled to continue through 1979.

It is apparent that considerable attention is being afforded the titanium fire hazard problem. Direct engineering/material solutions certainly will be forthcoming. In the meanwhile the approach being pursued by the CAA should provide continued safeguard that such incidents should they occur, shall not have cascading fire effects which jeopardize aircraft survivability. The Working Group strongly endorses this approach.

5.4.2 Fuel System

Inflight fuel tank fire and explosion must always be considered a serious hazard because of the catastrophic effects on passenger and aircraft survivability. Although the frequency of inflight fuel system fire and explosion, fortunately has been low, the serious consequences of such occurrences have been substantiated. Major inflight fuel tank ignition threats include lightning strikes, electrical equipment failure, flame impingement due to external fires e.g. fires in adjacent engine installations, and penetration by metal fragments emanating from uncontained engine rotor failure. The catastrophic occurrences, based on Subgroup I's review, have involved Jet B (JP-4) fuel or mixtures of Jet B and Jet A type fuels. These provide a greater likelihood of flammable vapor-air mixtures being present in the tank under subsonic flight operations. In view of the fact that a major portion of the world-wide civil transport operations utilizes Jet A type fuel, the aforementioned mishap experience implies an inflight fire safety advantage for such a lower volatility fuel. More importantly the Working Group considers the excellent operational experience to be indicative of the effectiveness of lightning protection, engine debris avoidance criteria, and electrical system design measures which have been applied to operational aircraft. Continued emphasis of prevention of ignition source ingress into fuel tank areas must continue to be stressed particularly with regard to any new structural materials such as composite materials proposed for use in fuel tank areas.

Additional protection techniques are available or under development which if applied to transport aircraft could further reduce the prospect of fuel tank inflight fire and explosion involvement. These include in-situ baffle foams, inerting with nitrogen, and use of chemical suppressants all of which as discussed previously under 5.3.1.3 entail significant weight and/or logistic and cost penalties for implementation. Current development activities being pursued in France and the United States in the area of on-board inert gas generation systems based on permeable membrane separation techniques offer good potential for reducing aircraft system penalties for such protection. These technology efforts should be continued. In the final analysis application of such additional protection will become attractive only if it provides a benefit to a variety of aircraft fire scenario problem areas. In this regard, the on-board inert gas generation approach in the assessment of the Working Group offers such a potential. A system can be visualized where, in addition to tank inerting, the nitrogen-enriched air could also be utilized for combatting inflight fires occurring in high risk cabin areas, cargo compartments, wheel bays and propulsion installations. In essence an integrated total aircraft fire suppression system may be realizable.

As with any additional protection approach once it is demonstrated to be airworthy and reliable actual implementation will necessitate international acceptance and endorsement as a mandatory requirement.

5.4.3 Aircraft Cabin

Fire in any inhabited confined space is always potentially catastrophic. When a fire occurs under conditions where escape is not possible, such as in an aircraft

cabin area while inflight, the probability of a catastrophic ending becomes even greater. The habitable dwelling fire problem obviously is not unique to aircraft as evidenced by the daily occurrence of house fires, the oxygen enriched atmosphere space vehicle and test chamber fires experienced in the Space Program, and fires on-board other modes of transportation such as naval ships. The basic answer to all of these situations is similar and is dependent on the application of sound fire prevertion, fire isolation and containment, smoke and fire detection, and adequate fire extinguishment and control capabilities. The extent to which each of the above fire protection engineering elements is applied will vary with the nature of the specific potential fire hazard scenario and the assessment/definition of what is considered an acceptable level of risk. The specific best engineering approach as a consequence will not be the same in all instances. Considerations must be given to the nature of the combustible materials and fuels present; their distribution; their ignition and flame propagation characteristics under various placement conditions; the nature of the by-products formed when degraded, pyrolyzed and burned; their heat release characteristics; their susceptibility to ignition by various thermal, electrical, mechanical, and chemical means; the nature of the smoke generated in terms of degradation of visibility; techniques suitable for sensing or providing early warning of any hazardous reaction occurring; their response to various potential fire extinguishing/fire suppression agents and techniques at various stages in the burning process; interaction effects of a multiplicity of materials being present in the environment; any changes in material response in normal atmosphere to that in the high realism fire environment atmosphere, etc. The problem in terms of these considerations is not an easy one, and possibly because of the apparent complexity, the natural tendency is to look for complex solutions, when in most instances the best solution may only require a simple approach.

In the aircraft cabin inflight fire scenario, at least in the case of passenger carrying aircraft, we are faced with a confined space provided with a life support/ environmental control system which under the usual operating conditions is capable of handling the demands placed on it. Within this confined space there are also interior wall and ceiling materials, furnishings, food and alcoholic beverages, a variety of throw away products (paper towels, cups, etc.), blankets and pillows, and variety of carry-on items. Electrical power is distributed throughout the interior area and smoking of cigarettes is permitted in designated areas. Principal ignition threats are electrical and thermal in nature and, with the exception of food preparation areas, will trigger initially small fire threats which if unaccessible or not detected depending upon the proximate combustible loading, will grow in intensity, propagate and result in a rapidly deteriorating internal environment. In this situation human survival is not first threatened by direct flame or excessively high temperature gas exposure, but rather from the debilitating and eventually fatal toxic gases which are generated. The aircraft environmental control system is not capable of providing a sufficient number of cabin air change per minute to significantly deter toxic and smoke product buildup. Loss of good visibility conditions due to smoke, although no doubt emotionally disturbing does not pose the threat to passenger survivability inflight. Loss of visibility can seriously hamper fire fighting efforts of crew members. Degradation of visibility in the cockpit also obviously jeopardizes survivability from the standpoint of the crew being able to maintain flight control. If the localized combustion process continued unabated, the pyrolysis products building up within the cabin eventually become vulnerable to a process normally referred to as "flash-over." This process is basically the rapid gas phase propagation of flame through the cabin resulting in an immediate temperature rise, rapid consumption of available oxygen, and possible internal over pressurizaton and rupture (explosion) of the cabin. The occurrence of "flash-over" can be viewed as the endpoint of any survivability opportunities.

There are several major factors essential to the threat assessment and identification of best risk reduction approach. These are:

(a) The scenario is a habitable confined space from which no inflight egress is possible.

(b) The combustion threat is largely associated with solid materials. Fires can be expected to initially be low order and, given enough time, can progress to flash-over. Compared to liquid fuel fires, the opportunity for fire interdiction from a time standpoint is much greater.

(c) The time element for a given fuel loading configuration will vary with the size of the habitable compartment. This is depicted in Table 5.1, in a very simple manner, for the case where a cellulose (paper) material is the fuel. It will be noted that as the confined volume increases more fuel has to be consumed to achieve the same endpoints. This translates into the conclusion that the larger the compartment the more time is available for effective counteraction.

(d) Because of fuel loading and ignition sources availability, certain areas inherently will pose a greater threat than others. These areas must be identified early and effective threat reduction accomplished.

(e) The initial threat to passenger survival is not the receipt of fatal burns but rather being overcome by toxic gas/smoke products. This demands that an

adequate emergency life support capability be available which can provide unvitiated breathing air/oxygen. Because of the large quantity of carry-on combustibles, this emergency life support capability must be available no matter what progress is made toward fire-proof, toxic product free interior cabin materials.

(f) Sufficient first-aid fire extinguishing capability must be available to effectively cope with accessible in-flight fires. Areas which are isolated, not always occupied, or pose an inherently higher fire threat potential should be protected with a hazard detection and fixed fire extinguishing system.

(g) Inflight smoke is a serious impairment to those attempting to effect fire control and to the crew who are endeavoring to maintain flight control. Special protective measures and in the case of the crew special cockpit smoke abatement design considerations should be provided major emphasis. With regard to passengers, as long as a safe, breathable source of air or oxygen is being provided, smoke and its visibility impairing effects, at least while inflight, is not of major concern.

As a consequence of the above consideration, the Working Group suggests that perhaps some major realignment of areas warranting research and development emphasis in terms of the near-term problem is required, specifically for the current aircraft threat:

(a) Immediate emphasis is required toward providing an emergency, unvitiated air or oxygen individual life support capability. To the extent feasible the approach could be a life support hood, as suggested in the survivable impact fire scenario, for dual purpose utilization. The standardized emergency procedure should entail the donning of such hoods at first indication of an interior cabin fire problem.

Obviously for current operational aircraft practical realization of the emergency life support requirements can be accomplished by deployment of existing individual oxygen masks. Currently there exists considerable reluctance to deploy these masks under cabin fire conditions because of the concern over fire intensification due to oxygen enrichment. Although localized oxygen enrichment in the vicinity of the user will occur, overall cabin enrichment under conditions of use in the judgment of this Working Group will be minimal. For example, as previously indicated by the National Academy of Sciences, under the most ideal conditions only 2-3 volume percent increase in oxygen content would be possible assuming that no human and fire consumption, or loss due to external leakage or ventilation occurs. Because of the importance of this matter to preservation of life, it is recommended that an immediate in-depth analysis and risk assessment, substantiated as necessary by appropriate high realism cabin fire simulation testing, be conducted to establish standardized emergency procedure with respect to "use" versus "non-use" of oxygen masks.

(b) High risk areas such as food preparation areas and lavatories should receive direct fire protection system coverage if not already incorporated. This should include early detection and adequate type and quantity of fire extinguishing agent via a fixed system approach. Where feasible, such as in lavatory areas, use should be made of available water via a water fog fire suppression system. Storage and disposal of combustibles should be provided in isolated fire-proof containers or storage bins.

(c) Smoking on the part of passengers and crew should be either banned or limited to special areas in the aircraft. Strict enforecement of rules against smoking while in aisles, lavatories, etc., should be effected. Improved conscientious response on part of passengers could be accomplished by more emphasis on education of the public to assure awareness of the potential threat and the "why" for emergency actions which may be required.

(d) Special engineering attention should be provided to the modification of the crew-cockpit area to prevent or minimize smoke ingress from external areas. A possible solution might entail the incorporation of an emergency ventilation system which provides positive air pressure within the crew portion of cabin area.

(e) Near-term emphasis, including operational aircraft, should be provided to the introduction of low hazard (flame propagation, sustenance and smoke and toxic products formation) potential materials in high risk areas (galleys, lavatories, insulated internal ducting). This activity should be viewed as an adjunct to the emergency life support and fire control actions suggested above.

(f) With respect to the characterization of the hazardous flammability and by-product generation properties of materials, the Working Group suggests that perhaps more emphasis is required in quantizing fire behavior under selected critical hazard scenarios utilizing currently approved materials and high realism and well instrumented aircraft cabin test articles with animal exposure. Testing should include typical carry-on combustible loading and internal cabin ventilation conditions. Effects of emergency oxygen deployment on fire severity could also be established. Results of these tests should be utilized to define specific property improvement requirements (flame spread; oxygen index; smoke generation; toxic by-products) needed to reduce risk to an acceptable level. Direct comparison of compartmentation, isolation and protection systems (detection, suppression) versus materials hardening should also be performed.

Advanced emergency life support systems should also be evaluated. Trade-off studies of various protection enhancement techniques should be conducted for selection of optimal-lowest cost, minimal penalty engineering solution to the interior cabin fire survivability problem.

TABLE 5.1 - Maximum Fuel Consumption in Air Versus Closed System Volume and Initial Pressure

Volume	$10.2m^3$	($360\ ft^3$)	$204m^3$	($7200\ ft^3$)	$1529m^3$	($54000\ ft^3$)
Pressure, ATM	1	0.67	1	0.67	1	0.67
Oxygen Content (Kg)	2.9	1.95	58.1	38.6	435	290
Fuel	Cellulose (Heat of Combustion 1.67×10^7 j/Kg)					
Maximum Burnable* Fuel (Kg)	1.22	0.82	24.5	16.3	184	123
Maximum Theoretical Flame Temperature (°C)**	2066	2066	2066	2066	2066	2066
Maximum Pressure Ratio (P Final/P Initial)	8	8	8	8	8	8
Maximum Final Pressure, ATM	8	5.4	8	5.4	8	5.4

* Assumes All But 10 Volume Percent O_2 Can React
**Does Not Consider Dissociation of Product Gases

5.5 Ramp Fire Protection

The ramp scenario relates primarily to aircraft while in the parked mode. The aircraft could be attended or unattended and, as manifested by past experience, is still highly vulnerable to fire. Principal triggering mechanisms for example could include static electricity generation during fuel servicing, electrical malfunctions, hot brakes, and failure of maintenance, servicing personnel to adhere to prescribed safe procedures.

In general, recent fuel servicing experience for transport aircraft with both Jet A and Jet B fuels has demonstrated that current fuel system design and fuel loading standards are effective. The use of static dissipator additive in a major portion of the worldwide flight operations has provided an added margin of safety. Recent fuel system static electricity problems have primarily involved military aircraft employing internal polyester polyurethane explosion protection baffle material. Incidents which have occurred have primarily entailed low order internal flash-fires and localized minor damage. Recent investigations indicate that high velocity fuel impingement on these baffle materials results in localized static electricity discharges which under proper fuel-air mixture conditions result in ignition. Corrective measures include modification of fuel inlet discharge design criteria and, depending on type of baffle material, utilization of static dissipator additive.

In addition, past experience also indicates that vulnerability to static electricity induced fuel tank hazards is less with straight lower volatility (Jet A type) fueling operations. This reduced vulnerability is due only to the volatility characteristics of the Jet A type fuel since both fuel types have similar charging characteristics.

In the case of landing gear fires, although many occur during aborted take-off conditions, experience with the phosphate ester fire resistant fluids has overall been good. There are conditions, however, where even these fluids can be involved in sustained, damaging fire response. Accordingly, further research on less flammable, or preferably nonflammable hydraulic fluids is warranted possibly for selective use in high fire risk areas. Current development activities being pursued by the Navy and Air Force in the United States offer some potentially promising candidate fluids; this work should be continued. Incorporation of sensors to monitor tire pressurization prior to take-off and thereby prevent unnecessary tire failures which could contribute to hydraulic fluid fire involvement should be pursued.

When aircraft are unattended consideration should be given to the provision of portable automatic cabin fire detection and extinguishment capabilities in order to avoid extensive fire damage from comparatively minor fires being permitted to continue unabated.

5.6 Material Flammability, Smoke and Toxicity Testing

Laboratory testing of material properties relative to fire, smoke and toxicity. provides an attempt to rate such materials and to provide an input into fire risk analysis. Being laboratory tests, they generally do not duplicate the scale of the actual equipment, the complexity of interdependent systems, and, usually, the complexity of the environment in which the materials are used.

Because of the limitations mentioned above, laboratory materials tests often fail to meet their objectives and, in some cases, lead to apparent contradictory results. In Section 3 of the report selected tests were reviewed and some of the deficiencies pointed out. The primary deficiency of all of the standard laboratory tests in use today, is the failure to provide theoretical models which permit interpretation of the test data in terms of the actual hazard. A list of numbers is of some use, but does not generally give enough information and, in some cases, may be misleading.

5.6.1 Fire Tests

5.6.1.1 Flash Point

For pure liquids, the flash point does provide a useful measure of the potential of a flammable vapor-air mixture at some ambient temperature. It does not, of course, measure the hazard associated with mists and sprays of the same liquid. Obviously, it is not intended to apply to mists and sprays. A more important deficiency is the failure of the flash point test, as normally run, to account for the change in flash point as a mixed fuel evaporates or ages. If a fuel contains a small amount of a volatile component, its hazard may be minimal in a large free space - the test might be too conservative. If the fluid contains a volatile inhibitor, water or a freon, the residue might have an undesirable flash point. Modification of the test to include various degrees of vaporization or a model to couple the flash point with a distillation or evaporation curve would extend the value of the test.

5.6.1.2 Autogenous Ignition Temperature

Hot surface ignition of gases and liquids has been one of the most misused and misunderstood of the various laboratory tests. The ASTM-ATM supposedly gives the lowest surface temperature at which a liquid will ignite and, if true, this could serve to define the upper allowable temperature limit of metal surfaces permitted. The test does not evaluate catalytic effects of surfaces including active metals, deposits, etc.

The usual ignition test involves a complex interaction between heat transfer, diffusion, and chemical reaction. The higher ignition temperature for gasoline than kerosene in the standard ASTM-AIT test may be due to the presence of very rich mixtures near the hot surface when a volatile fuel, gasoline, is tested. It is known that the relative ignition rating of gasoline and kerosene can be reversed in tests with flowing air. The development of a variety of modified hot surface ignition tests was made necessary by the deficiencies of existing tests.

5.6.1.3 Fabric Fire Tests

The area of fabric flammability testing is in more difficulty than the testing of gases and liquids. Sample size, orientation, preparation, ignition, ageing, etc., all can influence the results of tests of fabric flammability. The relative numerical values obtained in any test may have little relation to the behavior of the materials in a fire. "Self-extinguishing" fabrics in a test may burn rapidly in a fire and the rate of spread over a small sample may be unrelated to the behavior of the same material in its various applications.

5.6.1.4 Smoke Tests

The generation of smoke is usually considered apart from the toxicity and irritation associated with products of combustion. Little is actually known about the mechanism of smoke generation so that the tests are highly empirical in nature. The tests rate materials on the basis of a relative tendency to smoke as measured by a flame size, usually flame height, in a diffusion flame. Such measurements provide no information with respect to the quantity and density of the smoke. The NBS method measures smoke density in a specialized test, but the results are not easily extrapolated.

5.6.1.5 Toxicity Tests

Toxicity testing is generally accomplished by two different techques: chemical analysis of the material or its degradation products and exposure of animals to the same materials. While there are many uncertainties related to the interpretation of toxicity data of either type, there are also uncertainties associated with the generation of these products. The temperature, heat flux, sample conditions, etc., affect not only the quantity and rate of production of the various products, but also their chemical nature. Toxicity tests, therefore, must be performed in a manner that can be extrapolated to the full-scale problem, and must include various synergistic effects involving various materials. This is the major weakness in toxicity testing.

In summary all of the various types of tests should be reviewed in the light of modern experimental and theoretical techniques to determine whether better tests can be devised.

(a) The tests themselves should be of sufficiently fundamental nature so that the experiments can be described analytically. If they are not, they should be modified or new tests devised.

(b) Within practical cost limits, modern experimental methods should be employed to produce not a single number, but a behavior pattern; not only a lumped parameter, but a detailed structure.

(c) Analytical models and techniques should be developed to relate laboratory test results to the full-scale problem. The nature of the tests and their interpretation must be developed together. The laboratory test results must provide the input necessary for the analysis and, therefore, cannot be selected arbitrarily. It would be useful, in fact, to analyze a fire risk problem and establish the type of tests necessary to provide quantitative evaluations and comparisons.

(d) Government laboratories and large industrial laboratories should continue to develop large-scale simulation facilities to provide a bridge between small scale laboratory tests and the full-scale problem.

(e) Wherever possible, accident data and full-scale tests should be used to refine the analytical models and guide laboratory test development.

5.7 Concluding Remarks

In closing, the Working Group recognizes that it has addressed a variety of aircraft fire safety matters and recommended a number of actions which offer varying opportunities for fire safety enhancement. The realization of these potential advancement opportunities in a timely and resourceful manner ideally requires a cooperative international program approach. Unfortunately, to our knowledge, such an approach has no precedent even for other types of international concerns such as pollution of the environment, alternate energy sources, and advanced transportation systems. Realistically then, the embarkment upon such a program approach for the aircraft fire safety area would appear to be inherently prone to extreme difficulty. Nevertheless, some recent events already indicate a partial trend in the aforementioned direction. For example in June 1978 the Government of the United Kingdom of Great Britain and Northern Ireland, represented by the Procurement Executive of the Ministry of Defence (MOD(PE)) and the Government of the United States of America represented by the Department of Transportation, Federal Aviation Administration (DOT/FAA) entered into a Memorandum of Understanding concerning Co-operation in the Testing and Development of Anti-Misting Kerosene and Related Equipment. The purpose of the joint program is to reach an early decision whether anti-misting kerosene (AMK) is a potential candidate for certification or whether its ultimate use in commercial service is too improbable to justify further work. It is envisaged that a decision will be made before the end of FY80.

In a related manner in U.S. Federal Register, Volume 43, No. 165 dated August 24, 1978, the Department of Transportation, Federal Aviation Administration announced withdrawal of the following notices and advance notices of proposed rule-making:

(a) Notice No. 74-16 (30FR12260; April 4, 1974) entitled, "Transport Category Turbine Powered Airplanes Fuel System Explosion Prevention."

(b) Notice No. 74-38 (39FR45044; December 30, 1974)entitled, "Compartment Interior Materials Toxic Gas Emission."

(c) Notice No. 75-3 (40FR6506; February 12, 1975) entitled "Smoke Emission from Compartment Interior Materials."

(d) Proposed § 121.312(b) as set forth in proposal No 8-118 of airworthiness review program, Notice No. 75-31 (40FR29410; July 11, 1975) entitled, "Aircraft, Engine, and Propeller Airworthiness, and Procedural Proposals."

The above action was based on comments received in response to the notices and the FAA's determination that rule-making action based on the notices is not appropriate at the present time. Most importantly, however, with respect to the overall goal of improving post-crash occupant survivability, the FAA believes that a forum must exist to allow for the fullest and most effective participation of nongovernmental entities in the first stage development of a comprehensive regulatory program. Toward this end, the Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee, with opportunity for international participation, has been established. The establishment of this Committee in conjunction with ongoing research and development should enable the formulation of comprehensive standards, directed at improving post-crash occupant survivability, that will be both feasible and effective considering both their safety and economic consequences.

With respect to the overall Aircraft Fire Safety area, the Working Group suggests that an additional approach to cooperative action is to build upon what has already been

initiated via this NATO-AGARD sponsored activity. In this regard it is recommended that strong consideration be given to the establishment of an Aircraft Systems Safety Panel under AGARD to provide for continuity of attention to the safety problem; provide for a coordinated, resourceful follow-on research and development activity at least on a limited international basis; and assure the maintenance of a technical information exchange posture and the conduct of selective specialists conferences on key elements of the overall problem. A Safety Panel comprised of appropriate interdisciplinary representation is visualized to assure a suitable integrated engineering approach since fire safety is only one element of any overall system safety assessment as has often been implied in this Working Group II report.

APPENDIX A

AGARD

Propulsion and Energetics Panel

Terms of Reference

Working Group II

Aircraft Fire Safety

Objectives:

Aircraft are inherently vulnerable to a variety of fire and explosion threats which can be encountered throughout their total operational utilization regime encompassing maintenance, ground servicing, in-flight, crash and combat. Protection against these threats requires the implementation of fire prevention, containment/hardening, detection and active and passive extinguishment/suppression and control techniques. The extent to which protection measures are incorporated is dependent upon a valid quantitative assessment of the fire risk, confidence in the ability of a specific protection measure to counteract the risk and willingness to accept the cost and weight penalties associated with its adoption for operational aircraft. Presently many inadequacies/controversies exist which prevent valid cost/benefit trade-off studies to be performed and to enable identification of technological activities which should be emphasized.

It is intended to analyze aircraft fire safety experience under various internal and external threat conditions and methods of reporting fire incidents, identify specific areas where fire protection methodology is inadequate, and to delineate future technological possibilities that offer significant opportunity for enhancement of aircraft fire safety and personnel survival.

Scope of Work:

a. Form a working group of experts from NATO countries.

b. This working group will then select major elements of the aircraft fire protection problem for comprehensive assessment. These could include:

1. Propulsion/Accessories Compartments
2. Interior Cabin and Cargo Compartments
3. Fuel/Hydraulic Systems
4. Aircraft Crash Fire Protection
5. Ground Servicing Equipment (particularly that related to fuel handling)
6. Combat Survivability

c. Collect accident/incident/combat mission experience from the NATO aviation community supplemented, where possible, with broad international experience, in particular to establish:

1. Methods of reporting all fire and explosion incidents.
2. Adequacy and deficiencies of flight fire safety standards.
3. Reliability and performance of operational fire and explosion protection equipment.
4. Adequacy of emergency procedures for enhancing personnel survival against interior cabin fires.
5. Influence of fuel volatility on susceptibility to fire and post-crash passenger survivability.

d. Identify specific technological opportunities which could be applied to counteract high risk fire safety deficiencies. These opportunities will include test methodology, design criteria, and specific fire protection measures. A distinction will be made between normal flight safety and specialized combat survivability applications.

e. Recommend possible basic and applied research activities either to clarify regions of uncertainty or to evolve new techniques for coping with established flight fire safety threats.

Result of Work:

An AGARD Advisory Report will be written that will summarize the findings of the Working Group in specific technical areas. The report will include recommendations

with respect to reporting fire incidents, flight fire standards, protective equipment, necessary research and development work, etc.

Time Schedule:

Begin September 1976
Finish September 1978

Recommended Definition of Sub-Groups:

a. Subgroup I - Experience Factor

1. Analysis of military-civilian aircraft fire experience based on available accident/incident data. This problem/task will probably require independent evaluation of military and civilian experience because of the significant differences in the type of aircraft and mission requirements. The analysis will address accident/incident experience under normal/natural and combat operational environmental experience.

2. The data to be acquired should enable analyses of and lead to conclusions with respect to the various sub-elements of the overall Aircraft Fire Safety Record. The sub-elements should include: mission mode, crash location, location and source of inflight non-crash induced fires, inflight fire fatalities, aircraft crash fires (fuel type, ignition mode, fire versus total fatalities), type and speed of response to aircraft fire fighting and rescue operation and aircraft fire incidents in which fire prevention design and protection measures performed effectively.

b. Subgroup II - Fire Protection Factor

This task will have as its purpose to quantify to the extent possible the fire scenarios associated with various aircraft on-board and crash associated mishaps and to address the engineering, design and regulatory approaches, models and techniques used to counteract the fire threat. The intent will be to categorize the principal unwanted combustion possibilities in terms of specific engineering parameters which provide a measure of their damage potential. These unwanted combustion scenarios should encompass the natural and hostile environment operational areas and include isolated fire eruptions such as in engine bays, wheel wells, crew/passenger areas as well as massive fire/explosion eruptions in fuel tanks and crashes. This subgroup could be divided further into three sections: Combustion Hazards of Aircraft Material (Fire Dynamics and Vulnerability); Fire Protection Engineering; and Aircraft Crash Worthiness.

NOTE: As discussed in Section 1 in the main body of this report, the Working Group with concurrence of the Propulsion and Energetics Panel organized itself into the following Subgroups:

Subgroup I - Aircraft Accident/Incident Fire Experience

Subgroup II - Aircraft Materials Combustion Hazards

Subgroup III - Aircraft Fire Protection Engineering

In addition major focus was placed on turbine powered transports under natural flight environment conditions. The time schedule was modified to begin December 1976 and finish by December 1978.

APPENDIX B

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APPENDIX C

List of Meetings

I. First Meeting of AGARD PEP Working Group 11 - U.S. Trade Center, Paris, France, 9-10 December 1976.

Objectives:

(1) Review, Modify PEP - Terms of Reference

(2) Finalize Subgroup Organization Structure

(3) Assignment of Representatives to Subgroups

(4) Designation of Subgroup Leaders by Members

(5) Develop Subgroup Mission Statements

(6) Assignment of Specific Subgroup Task Activities to Individual Members

(7) Documentation of Tasks and Coordination of Schedule Requirements

(8) Procedures for exchange of data amongst participants

(9) Establish Tentative Dates and Locations for Future Meetings

II. Second Meeting of AGARD PEP Working Group 11 - Office National d'Etudes et de Recherches Aerospatiales (ONERA), Paris, France, 25-28 October 1977.

Principal objective was to permit direct individual interactions at Subgroup and overall Working Group levels with emphasis on working sessions. Subgroup working sessions placed emphasis on review of individual participant progress, collation of information, identification of critical gaps, identification of R&D activities in progress which address these gaps and identification of preliminary recommendations. Status reports from the Subgroups were interspersed in meetings of the entire Working Group to permit broader exchange of information, assure total membership agreement with approaches being pursued, and *identify additional fire safety problem areas*. Working Group sessions were also held to coordinate future meetings, schedules and the format and content of the final advisory report.

III. Third Meeting of AGARD PEP Working Group 11 - Government Conference Center, Ottawa, Canada, 23-26 May 1978 (all members), 27-28 May 1978 (Leaders, Staff, other interested members).

This was the final planned assembly of the entire Working Group. Major effort was directed toward finalization of the Subgroup reports in rough draft form. In addition overall Working Group positions on various facets of the Aircraft Fire Safety Problem were formulated. Plans for compiling a Preliminary Draft of the Working Group Advisory Report for review by members and other NATO Government organizations and industry designated by the Propulsion and Energetics Panel (PEP) were finalized. In addition the Working Group agreed to the conduct of a Round Table discussion in conjunction with the 52nd meeting of the Propulsion and Energetics Panel scheduled for late October 1978 in Cleveland, Ohio, USA. The Round Table discussion was to be for the purpose of direct interchange of information and viewpoints between Working Group representatives and those who had been designated by PEP to review the draft report as well as any other interested parties who subsequently indicated a desire to attend. It was agreed that at a minimum the Working Group Technical Director and the Subgroup Leaders would participate.

IV. Round Table Discussion - October 24, 1978, held in conjunction with PEP 52nd Meeting Bond Court Hotel, Cleveland, Ohio, U.S.A.

In addition to the Working Group Technical Director and the Subgroup Leaders several Working Group members from the United Kingdom, Canada and Germany participated. Other participants included representatives from: British Aerospace Aircraft Group and Cranfield Institute of Technology, United Kingdom; and General Dynamics (Fort Worth), National Aeronautics and Space Agency (Langley, Ames, Lewis and Houston Research Centers), and S. W. Foundation, U.S.A. Letter communication was also received from: the Royal Aircraft Establishment (Ministry of Defence - Engineering Physics and Materials Departments) and the Civil Aviation Authority of the United Kingdom; and the General Electric Co. (Evendale), Air Force Aeronautical Systems Division (Deputy for Engineering), and Detroit Diesel Allison of the United States.

On the basis of the Round Table discussion and the written comments the content of the draft Advisory Report appeared to be generally favorably received and to provide a meaningful assessment of the current aircraft fire safety posture as well as the potential future opportunities for fire safety enhancement. Major concerns with the report and or additional elements of the fire safety problem identified as possibly warranting attention were as follows:

(1) Updating the bibliography, particularly in the materials and the antimisting kerosene areas would be beneficial.

(2) The report appeared to be mainly concerned with long term solutions. There is a need to study the possibilities of reducing risks on existing aircraft within reasonable economic bounds. Similarly, the long term solutions are unlikely to be available for the next generation of transport aircraft so that there is a need for an interior position based on current knowledge to be established, not necessarily in terms of airworthiness requirements, but preferably in the form of acceptable practices, particularly in the areas of cabin fires, based on the current state-of-the-art.

(3) A prevalent cause of ramp fires, particularly on unattended aircraft or aircraft being serviced has been electrical, and has several times resulted in extensive damage. The mechanisms of the ramp fires require further study. Similarly, concern was voiced with respect to fires occurring during the oxygen charging.

(4) Further study was considered warranted on the effects of aging in the ignition, flame spread and smoke and toxic products formation of current and candidate future interior cabin materials, particularly those utilized in high risk areas. Material specifications should include aging performance evaluation. Additionally, means to simply remedy material mal-aging fire risk effects for example by intumescent paints and other coatings should be pursued.

(5) Caution was expressed concerning the proposed reconsideration of air aspirated smoke hoods during impact survivable post-crash fire scenarios. Specific concerns include the ability of the passenger to do the right thing, the need for different sizes, and the difficulties and potential loss of time when fitting especially in emergency.

(6) The report does not consider improvements to the evacuation assistance for passengers after the aircraft has crashed; such things for examples as:

(a) improved protection of cabin crew so that they are better able to assist

(b) training of cabin crew in evacuation procedures

(c) emergency lighting and marking of exit routes and availability of emergency equipment

(d) design of seats to prevent injury and retention of loose articles

(7) In view of the comprehensive nature of the report it was suggested that the final version be modified to a consistent format for each Subgroup report and overall streamlining be accomplished to permit easier use by interested reader.

As a result of the feedback obtained the Working Group felt that some editorial polishing up of the report was warranted, however, the varied subgroup reporting inputs should be maintained to preserve the "true" Working Group flavor of the report. The Technical Director was tasked with restructuring the report where appropriate without making a major project out of the endeavor.

The other technical comments identifying additional needs are considered very valid and worthy of future study. Additionally, many near-term improvements for current aircraft fire safety may be possible. It is not the intent of this Working Group to specify particular approaches but rather to strongly endorse and foster the in-depth analysis and mutual agreement by appropriate international industry, Government and user representatives as to what specific improvements should be implemented.

Basically as a result of the Round Table discussion the Working Group's overall recommendations and conclusions remained unchanged. We are grateful to all who participated at the Round Table discussion and also to those who were unable to attend but provided written comments.

APPENDIX D

Section I (General)

Airworthiness Requirements/Engine Blade and Rotor Containment

Chapter C1-1
General

Sub-Section C1-
General and Definitions

3 EQUIPMENT

3.1 Group 1 Engine Equipment and Propeller Equipment

3.1.1 The equipment shall be designed to conform with specifications detailing the necessary Engine (or Propeller) airworthiness requirements acceptable to the Authority. Conformity with the specifications shall be certified by an Organisation approved by the Authority for the purpose.

3.1.2 Unless the tests prescribed in C2-4, C3-4, C4-4, C4-6 and C5-4, as appropriate, will subject an item to such cycles of operation as to adequately represent all the critical conditions affecting its airworthiness to which it may be expected to be exposed during service, the equipment specification shall state those additional airworthiness requirements for which evidence of compliance will be needed (see C1-1 App., 1).

3.2 Group 2 Engine Equipment. The Engine/equipment interface requirements as they affect the Engine shall be identified by the Engine constructor in suitably referenced documents. Where any Group 2 equipment is to be in the initial Engine approval then compliance with these Engine/equipment interface requirements shall be established by the Engine constructor by tests or other acceptable means.

3.3 Equipment with High Energy Rotors (see C1-1 App., 2). Equipment with high energy rotors shall be such as to meet one of the following: -(a) failures will not result in significant non-containment of high energy debris, or (b) an acceptable level of integrity of the design, including the high energy parts, has been established, or (c) an appropriate combination of (a) and (b). (See Table (C1-1 App.))

APPENDIX TO CHAPTER C1 - 1

2 EQUIPMENT WITH HIGH ENERGY ROTORS (see C1 - 1, 3.3)

2.1 For equipment with high energy rotors, the requirements of Section C, with which compliance will have to be shown, is dependent on the category of containment which has been demonstrated.

2.2 As an example, Table 1 (C1 - 1 app.) shows four containment categories relating to a turbine-starter having air or gas supplied from an external source and specifies the requirements appropriate to each category. Other equipment will be considered on a similar basis, using the fault analysis of the whole system to determine the critical speeds which may result from failures.

TABLE 1 (C1 - 1 App.)

CONTAINMENT CATEGORY DEMONSTRATED	SECTION C REQUIREMENTS APPLICABLE (See Table 2 (C1 - 1 App.))
1. Blade containment only	a, b, c, d, e and f
2. Tri-hub burst within the normal operating speed (i.e. at the highest permitted speed without failure of the system but including maximum governor overswing)	a, b, c (a reduction of the fatique scatter factor may be permissible), d, e and f
3. Tri-hub burst at the maximum "no-load" speed, under all fault or combination of fault conditions (including those affecting fluid supply) other than extremely remote fault conditions	a and b
4. Engine-driven case if more critical than 3, Hub burst containment at the maximum driven speed or the maximum burst speed, whichever is the lesser.	a only

TABLE 2 (C1 - 1 App.)

REFERENCE (see Table 1 (C1 - 1 App.))	REQUIREMENT
a	Quality control of containment means
b	Establishment that drive mechanism will prevent the Engine driving the starter to a dangerous speed, unless such a probability is extremely remote (see C3 - 2, 3.1.5)
c	Establishment of safe life (C3 - 2, 1.2.3)
d	Quality control of rotating parts (see C3 - 2, 1.2.4)
e	Integrity test of rotating parts (see C3 - 4, 22)
f	Clearance between rotating and fixed parts (see C3 - 2, 1.2.5)

Section 2

Chapter D4 - 1 General | Design and Construction | Sub-Section D4 - Design and Construction

15 HIGH ENERGY ROTORS; NON-CONTAINMENT OF DEBRIS

15.1 Gas Turbine Propulsion Engines and Auxiliary Power-units (see D4 - 1 App No. 6). Unless containment of debris is assured, design precautions shall be taken to minimize the probability of catastrophe being caused by non-contained debris in the event of an engine rotor failure. To this end an analysis shall be made of the complete aeroplane design (structure, essential components, systems etc.) to predict:

(a) the single and multiple failures that could result from the release of engine debris as defined in an agreed model (see D4 - 1 Appr. No. 6.1.3) that could prove catastrophic.

(b) for each such failure, the probability that catastrophe would result.

15.2 Equipment Incorporating High Energy Rotors. Unless there is reliable assurance that such rotors will not fail, such equipment shall either be demonstrated as capable of containing a failed rotor, or be so located that failure will not affect the ability of the aeroplane to continue safe flight.

APPENDIX NO. 6 TO CHAPTER D4-1 ISSUED, 1st OCTOBER, 1976

HIGH ENERGY ROTORS, NON-CONTAINED DEBRIS

1 GAS TURBINE PROPULSION ENGINES AND AUXILIARY POWER-UNITS
(See D4 - 1, 15) Where containment of debris is not assured it is acceptable to show compliance with D4 - 1, 15.1 on the basis described in this Appendix. The CAA may accept that the risks have been minimized, even though the levels of risk stated in 1.3 are not met, where the aeroplane is shown to have no features which provide significant hazard from this cause which could by practical design measures be avoided within the broad configuration and size of the aeroplane.

1.1 Because of the uncertainties present in any estimation of the probability of non-containment arising from individual engines, particularly those on which there is little or no service experience, all practical precautions should be taken to afford protection to the aeroplane and its systems against all forms of possible engine non-containment including debris different from that specified in 1.3.

1.2 Unless for the particular engine type concerned evidence can be produced to justify a different model, the analysis required by D4 - 1, 15.1 should show that the levels of risk specified in the model of 1.3 are not likely to be exceeded. These risk levels are the mean values obtained by averaging those for all discs on all engines assuming a typical flight. Individual discs or engines need not meet these figures, nor need they be met for each phase of flight provided that:

(a) No single disc shows risk levels averaged throughout the flight greater than twice those stated in 1.3

(b) Where failures would be catastrophic in particular phases of flight only, allowance is made for this on the basis of conservative assumptions as to the proportion of failures likely to occur in these phases.

The CAA would be prepared to consider a greater level of risk if the exposure exists only during a particular short phase of flight and conservative assumptions are made as to the likelihood of failure in the phase, e.g. in relation to engine conditions in that phase.

1.3 Model

1.3.1 Applicable to Whole Aeroplane

(a) Single One-Third Fragment. There is not more than a 1 in 20 chance of a catastrophe resulting from the release of a single one-third piece of disc.

NOTE: It should be assumed that the one-third piece of disc has a maximum dimension corresponding to the bladed disc radius, and the angular spread is +30° in relation to the plane of rotation of the disc. Where energy considerations are relevant, the mass should be assumed to be one-third the bladed disc mass, and its energy the translational energy (i.e. neglecting rotational energy) of the sector.

(b) Piece of Rim with Blades. There is not more than a 1 in 60 chance of a catastrophe resulting from the release of a single piece of rim with blades.

NOTE: It should be assumed that the piece of rim has a maximum dimension corresponding in half the bladed disc radius. The mass should be assumed to be 1/20th bladed disc mass or the mass of two blades complete with blade roots, whichever is the greater and its energy the translational energy (i.e. neglecting rotational energy) of the fragment. The angular spread to be assumed is ± 5° in relation to the plane of rotation of the disc.

1.3.2 Applicable to Duplicated or Multiplicated Systems Only

(a) Multiple Fragments. There is not more than a 1 in 10 chance of a catastrophe resulting from the release in three random directions of three one-third fragments of disc each having a uniform probability of ejection over the 360°, causing coincidental damage to systems which are duplicated or multiplicated.

NOTE: It should be assumed that each one-third piece of disc has a maximum dimension corresponding to the bladed disc radius, and the angular spread is +30° in relation to the plane of rotation of the disc. Where energy considerations are relevant, the mass should be assumed to be one-third the bladed disc mass, and its energy the translational energy (i.e. neglecting rotational energy) of the sector.

1.4 In complying with D4 - 1, 15.1 due allowance should be made in the analysis for delay before appropriate crew action is taken. Drawings showing the trajectory paths of engine debris and associated subtended angles of critical areas vulnerable to strikes should be provided. These would normally be restricted to front and plan views of the aeroplane and, where necessary, sectional drawings. The analysis should include, but not necessarily be confined to:

(a) damage to Primary Structure including the pressure cabin and airframe surfaces (e.g. deformation affecting aeroplane handling characteristics or operating range).

(b) damage to any other engine(s). Essential Services and Equipment (including essential indicating systems), particularly control systems for flight, engine power, and engine fuel supply isolation valves.

(c) flight crew incapacitance.

(d) penetration of the fuel system, especially tanks where this could result in the release of fuel into personnel compartments or any engine compartment or other regions where there could be a risk of fire or explosion.

(e) the risk of explosion resulting from penetration of the vapour space of fuel tanks.

(f) damage to the fuel system, especially tanks, resulting in the rapid release of a large quantity of fuel and the effect on aeroplane handling characteristics and operating range.

(g) penetration and distortion of firewalls and cowling permitting a spread of fire.

APPENDIX E

British Civil Airworthiness Requirements on Titanium Fires

The following is an extract from the British Civil Airworthiness Requirements pertaining to turbine engine titanium fires. These requirements have just recently been incorporated. The extract is from Chapter C3-2 and its Appendix.

1.3.3 (see C3-2 App., 2 and 3) The major rotating components of the Engine shall have adequate strength to withstand both the thermal and dynamic conditions of normal operation and any excessive thermal or dynamic conditions that may result from abnormal speeds, abnormal temperatures or abnormal vibration loads. (In assessing the abnormal conditions to be considered, account shall be taken of the failure analysis prescribed in 1.2.)

Chapter C3-2 Appendix (Sub-Section C3-Turbine Engines for Aeroplanes)

(d) The way in which the design minimizes potentially dangerous rubs by such methods as:--

(i) large interblade row clearances,

(ii) the provision of material in areas of potential rub which melts safely or otherwise clears the rub before ignition temperatures are reached, and which has sufficient depth to prevent direct rubbing between rotating and other parts of the Engine during maximum predicted rotor or casing deflections including those likely to occur in fault conditions,

(iii) not using titanium for adjacent rotating and static parts, i.e. avoiding titanium/titanium rubs,

(iv) attention to rotor movements under transient and bearing failure conditions,

(v) ensuring that any titnium features at the front of the Engine, e.g. entry guide vanes, are robust and unlikely to shed thin, easily-ignited sections.

3 Titanium Fires (see C3-2, 1.3.3)

3.1 Experience has shown that most titanium alloys used for manufacturing engine rotor and stator blades will ignite and sustain combustion if the conditions are favorable. In such cases, the Engine casings may be penetrated allowing expulsion of molten or incandescent material which could, depending on the installation, hazard the aircraft.

3.2 Unless the constructor can produce adequate evidence that titanium items in the Engine are such that they will not ignite or will not support combustion, the Engine design should be assessed for vulnerability to titanium fires. It will normally be assumed that a titanium fire is possible if stationary titanium material exists in areas where:--

(a) pressure will exceed 200 kN/m^2 (29.4 lbf/in^2); and

(b) relative air velocities are in excess of approximately 50 m/sec (150 ft/sec); and

(c) the geometry is such that relatively thin titanium sections exist which can be rubbed, directly or after shedding, by rotating parts. Stator blades of conventional design, of up to 15 cm (6 in) of aerofoil height, are regarded as falling into this category.

NOTE: Theoretical studies have attempted to describe the conditions for ignition and continued burning of titanium (using fundamental parameters) in more scientific terms but because many of the parameters can adopt quite variable and unpredictable values during a damage process the above arbitrary values chosen from actual experience appear to provide the best guidance.

3.3 Where the assessment of 3.2 indicates that the possibility of a titanium fire cannot be ruled out on the particular design, it may be possible to show that a titanium fire will be confined to areas within the Engine where it cannot present a hazard, if necessary by the provision of additional protection. Otherwise the Engine approval will be endorsed to the effect that:--

> "Some risk of non-contained titanium fires exists on this Engine design, and the Engine is thus approved only for use in aircraft where such fires are unlikely to be hazardous."

If the risk is dependent on specific circumstances (for example the danger only exists at low altitude) such curcumstances may also be stated.

3.4 Experience has shown that the following features can reduce the susceptibility of Engines to titanium fires and such aspects will be taken into account by the Authority in making judgments under 3.2.

(a) The type of alloy, i.e. its constituents other than titanium.

(b) Blade coatings which inhibit ignition or subsequent combustion.

(c) Coatings, on casings and other parts, which resist fire penetration but can if necessary accommodate rubbing. (The possibility of eutectic reduction of the casing melting point by reaction with coating materials should be considered.)

APPENDIX F

Glossary

Ablation - Removal of material by erosion, evaporation, or reaction for short term protection against high temperatures. The ablating material forms a thermal barrier to protect the base structure.

Accelerant - Substance used to initiate and develop a fire. Flammable liquids are the most common accelerants.

Actionable Fire - 1. Fire started or allowed to burn or spread in violation of law, ordinance or regulation. 2. Any fire that requires suppression.

Afterglow - Process of continued glowing combustion after flame has been extinguished - or - glow in a material after the removal of an external source of fire exposure or after the cessation (natural or induced) of flaming of the material.

Anoxemia - Anoxic state of the blood - reduction of the oxygen content of the blood below physiological levels.

Anoxia - Strictly, absence of molecular oxygen in living tissue cells; often used to indicate reduction of the oxygen content of the blood below physiological levels.

Arrhythmia - Absence of rhythm, applied especially to any variation from the normal rhythm of the heart beat.

Asphyxia - Unconsciousness resulting from anoxia or hypoxia and increased carbon dioxide in blood and tissue. See suffocation.

Autoignition Temperature - Temperature at which a material ignites spontaneously in air. See spontaneous ignition.

Autoxidation - Spontaneous oxidation in air at moderate temperature without visible combustion, often the precursor of spontaneous combustion. Also: auto-oxidation or spontaneous heating.

Blacken - To knock down flames, quench burning embers or wet down charred fuel.

Bladder Cell - Tank formed by a flexible bag which is contained in a rigid cavity.

Body of Fire - Intense mass of flame accompanied by heavy smoke indicating the center of a fire.

Burn - 1. To be on fire. 2. Area burned over by a fire. 3. Working fire. 4. Test fire. 5. Tissue reaction or injury resulting from contact with heat or other cauterizing agent. Burns of the first degree show hyperemia (redness); of the second degree, vesication (blistering); of the third degree, necrosis of skin and underlying tissues (charring).

Burnback - Flames traveling back over an area previously extinguished.

Burning Rate - Velocity at which a solid or liquid is burned, measured in the direction normal to the surface and usually expressed in inches per second. Also called regression rate.

Burning Velocity - Rate at which a combustion wave propagates into unburned gas. In steady state, flame such as a bunsen flame propagates at a rate that is balanced by the flow velocity opposing the propagation. For premixed flames, the velocity depends only on the initial conditions in the cold gas (temperature, pressure, and composition). For such one-dimensional systems the burning velocity can be identified with the *eigensolution* to the flame equations. This property is often used to characterize combustion systems. Also called: burning rate, flame velocity; propagation velocity. See also flame; combustion.

Burn Out - 1. To fail as a result of overheating or burning, as of an electronic component. 2. To deliberately burn the fuel between a control line and a wildland fire for the purpose of stopping its advance. Syn: clean burn; fire out.

Burnout - 1. Failure of a component due to overheating. 2. a. Building gutted by fire. b. Area burned over by a wildland fire. See also burn. 3. Time the fuel and/or oxidizer in a rocket is completely consumed.

Calorific Potential - Energy a material or element of building construction is capable of releasing by complete combustion. Of: potential heat value.

Carboxyhemoglobin - Product of reaction between hemoglobin and carbon monoxide. Abbreviated as COHb.

Charged - State of a building or a space filled with dense smoke and hot gases and in danger of becoming seriously involved in a fire.

Char - To form more or less pure carbon during pyrolysis or incomplete combustion.

Charring - Incomplete combustion. Formation by heating of more or less pure carbon during pyrolysis. See pyrolysis.

Cheyne - Stokes Respiration - Type of breathing in which respiration gradually and rhythymically increases in rate and depth, then decreases until all respiration ceases for half a minute or so, then begins again as before.

Cinder - Incompletely burned fragment.

Combustible - Capable of burning. NOTE: Most substances will burn under suitable conditions and in certain instances without oxygen. Iron or zinc, for example, will "burn" in chlorine. Aluminum will "burn" in nitrogen atmosphere, zinc in chlorine, and zirconium dust in carbon dioxide. In fire practice, the term usually refers to materials that will burn under normal conditions.

Combustible Liquid - Liquid having a flash point at or above 140°F. A Class III liquid according to the flash point classification scheme. See flash point; flammable liquid.

Combustion - (Abbreviated: Combust) Field or process of exothermic self-catalyzed reactions involving either a condensed phase fuel, a gas phase, or both. The process is usually, but not necessarily, associated with oxidation of a fuel by atmospheric oxygen. Condensed phase combustion is usually referred to as glowing combustion, while gas phase combustion is referred to as a flame. See also. Deflagration; Detonation and Explosion.

Combustion Chamber - Enclosed space in which controlled combustion takes place; e.g., a furnace, firebox or internal combustion engine cylinder.

Combustion Products - Gases and solid particulates and residues evolved or remaining from a combustion process. In general, the products include fire gases, flames, heat, smoke and residues.

Combustion Wave - Temperature and compositional microstructure associated with a propagating flame. Cf: flame front.

Common Hazard - Potential causes of fire, such as smoking, defective electrical circuits, heating equipment; distinguished from a special hazard, which is unique to a given industry.

Conflagration - Fire of large extent, with a moving front, involving a number of buildings on more than one block in an urban area, or Class E forest fire involving structures. In addition to extent, the fire must cross a natural man-made barrier such as a street, road or waterway to qualify as a conflagration. Cf: group fire; mass fire.

Continuity of Fuel - Degree of proximity of combustible materials; uniform continuity indicates that the combustible materials are physically in contact with each other, patchy continuity indicates that fuel is not connected.

Cool Flame - Flame in rich vapor; air mixtures of certain hydrocarbons below 450°C. The chemistry involves peroxy radicals and is related to two stage ignition.

Creeping Fire - Fire that burns with a low flame and spreads slowly. Also: smoldering, running fire, spotting.

Crib - Loosely laid structure of layered timbers, each layer at right angles to the one beneath it. Used to set fires for tests or drills.

Cutoff - 1. Fire wall, fire door or other barrier designed to limit fire spread. See fire stop. 2. The point at which a fire is halted.

Cyanosis - A bluish-purple discoloration of skin and mucous membranes, especially due to the presence of excessive amounts of reduced hemoglobin in capillaries, or less frequently to the presence of methemoglobin.

Deepseated Fire - Fire that has penetrated deep into bulk materials.

Deflagration - S[illegible] sonic gaseous combustion process propagating through unreacted material by con[illegible]ction, convection and radiation, with flame front and reaction products traveling in opposite directions. Also burning rapidly with intense heat and dazzling light. Cf: detonation.

Detonation - Supersonic combustion process with flame front and reaction products traveling in the same direction. There will always be the noise of a shock wave in a detonation but not necessarily rupturing effects of an explosion as a detonation can occur in either a free or confined space or it may not be of sufficient force to cause a rupture, e.g. a knock in an internal combustion engine. Cf: deflagration; explosion.

Diffusion Flame - Non premixed laminar flame the propagation of which is governed by the interdiffusion of the fuel and oxidizer. A candle flame is a typical example.

Dose - Quantity of a chemical substance or other biologically active agent, such as x-ray radiation, administered at one time or in a given interval.

Dyspnea - Shortness of breath, difficult or uncomfortable respiration.

Edema - Pressure in a biological tissue of a greater quantity of fluid than normal.

ED_{50} - Calculated dose of a chemical or other agent that is expected to produce a specified effect in 50% of the biological specimens exposed.

Explosion - Effect of a rapid exothermic combustion reaction occurring in an enclosed space, characterized by a catastrophic buildup of pressure and resulting shock wave. An explosion may be either a homogeneous self catalyzed reaction or a traveling combustion wave in a confining vessel. Cf: deflagration and detonation

Explosion Limit - Highest or lowest concentration of a flammable gas or vapor in air that will explode when ignited.

Explosion Suppression - A method, device, or system to effectively extinguish an explosion after ignition but before the buildup of pressure to above design limits of the fuel tank or other compartments subject to explosion.

Explosive - Substance capable of sudden high velocity reaction with the generation of high pressures. Explosives are classified as deflagration (low explosive) and detonating (high explosive).

Explosive Mixture - Mixture of gases or vapors in the proportion in which they combine. Upon ignition, the entire mass combusts rapidly.

Explosive Range - Flammability range.

Exposure - 1. a. Portion or whole of a structure that may be endangered by a fire because of proximity and other factors. b. Likelihood of fire hazards. 2. A surface receiving energy from a heat source as the side of a hill facing the sun.

Extension of Fire - Spread of fire to areas not previously involved.

Extinguish - To put out flames. To quench a fire.

Extinguishant - Extinguishing agent.

Extinguisher - Portable device for putting out fires. NOTE: Fire extinguishers are given class designations corresponding to the classes of fires against which they are effective. See fire classes and extinguishing agent.

Extinguishing Agent - Substance used to put out a fire by cooling the burning material, inhibiting chemical reaction and/or blocking the supply of oxygen. The principal extinguishing agents are water; carbon dioxide; dry chemicals; foam; and vaporizing liquids (halogenated compounds). Syn: Extinguishant

Fire - Rapid oxidation of fuel in air resulting in heat and light.

Fire Brand - Hot, flaming or glowing solids, generally of cellulosic material, raised by strong convective currents and carried by high winds in large scale fires.

Firebreak - 1. An open space between stacks of combustible materials to prevent the spread of fire. 2. A natural barrier or cleared and sometimes plowed strip of land in a forest serving the same purpose.

Fire Barrier - A partition which will resist flame penetration under the most severe conditions of fire likely to occur at its location, e.g. firewall.

Fire Classes - For purposes of identification of hazards and to facilitate the control and extinguishment of fires, the fire service classifies fires and hazards by type of fuel or combustible:

Class A - Ordinary combustibles such as wood, cloth, paper, rubber, and certain plastics.

<u>Class B</u> - Flammable or combustible liquids, flammable gases, greases and similar materials.

<u>Class C</u> - Energized electrical equipment.

<u>Class D</u> - Combustible metals, such as magnesium, titanium, zirconium, sodium or potassium.

Fire Climate - Composite pattern of weather elements over time that affect fire behavior in a given region.

Fire Concentration - 1. Several fires burning in the same locality. 2. Sometimes the rate of fire occurrence per unit area.

Fire Control - Overall program of fire protection and suppression for reduction of fire losses as well as control of individual fires.

Fire Cutoff - <u>Fire stop</u>.

Fire Damage - Loss caused by fire such as property destruction or business interruption.

Fire Damper - Device installed in ventilating ducts or bulkheads to restrict the passage of fire. Normally kept in the open position, it can be arranged to close automatically or manually in case of fire.

Fire Death - Fatality resulting from a fire injury within one year after the fire.

Fire Detector - Device for automatically detecting the presence of abnormal levels of heat, smoke or invisible products of combustion. Used in conjunction with other devices to perform auxiliary functions, such as sounding an alarm, actuating an extinguishing system, shutting off fans or closing dampers.

Fire Devil - Small, rapidly whirling vortex of flame; from hot gases rising and cool air rushing into the low pressure area.

Fire Endurance - Measure of the elapsed time during which a material or assembly continues to exhibit fire resistance under specified conditions of test and performance. As applied to elements of buildings, it is usually measured by the methods and to the criteria defined in ASTM Method E-119, Fire Tests of Building Construction and Materials; ASTM Method E-152, Fire Tests of Door Assemblies; or ASTM Method E-163, Fire Tests of Window Assemblies. Cf: <u>Fire resistance</u>

Fire Exposure - Subjection of a material or construction to a high heat flux from an external source, with or without flame impingement.

Fire Flow - Flow rate of water in the mains of a given area required for fire protection in addition to the normal water consumption for that area.

Fire Gas - Gaseous products of combustion such as carbon monoxide, carbon dioxide, hydrogen sulfide or nitrogen oxides. Syn: <u>flue gas</u>.

Fire Load - Potential heat release of combustible materials in a given space, expressed in terms of Btu/sq. ft. (British thermal units per square foot) or, in the case of ordinary combustible materials such as wood and paper, in terms of lbs. sq. ft. (pounds per square foot). A fire load of less than about 80,000 Btu/sq. ft. (10 lbs./sq. ft.) is considered to provide a low fire severity in the space; 80,000 - 160,000 Btu/sq. ft. (10 - 20 lbs./sq. ft.), a moderate fire severity; and over 160,000 Btu/sq. ft. (over 20 lbs/sq. ft.) is considered to be a "heavy" fire load, providing a high fire severity. Syn: <u>fire loading</u>, <u>fire load density</u>. Cf: <u>potential heat value</u>

Fire Point - Lowest temperature at which a liquid gives off sufficient flammable vapor to produce sustained combustion after removal of the igniting source. Cf: <u>flash point</u>

Fireproof - A condition in which structure, equipment, wiring, controls, or piping is capable of performing its intended function under the most severe conditions of fire likely to occur at its location.

Fire Propagation - Spread of fire.

Fire Protection - Theory and practice of reducing life and property loss by fire, fire extinguishment, fire control and fire prevention. Narrowly the field concerned with the detection and extinguishment of fires.

Firer - 1. One who kindles or tends a fire. 2. One who discharges a firearm.

Fire Reaction - Response of a material in contributing by its own decomposition to a fire to which it is exposed.

Fire Resistant - A condition in which structure, equipment, wiring controls, or piping is able to perform its intended function under the most severe conditions of fire likely to occur at the particular location for a period of at least 5 minutes.

Fire Resistance Rating - Length of time, in hours, that a building material or assembly (beam, girder or truss; column, floor or floor-ceiling; roof or roof-ceiling, or wall or partition) will withstand the effects of the standard fire exposure and meet specific conditions of acceptance, as determined by a fire test conducted in accordance with the "Standard Methods of Fire Tests of Building Construction and Materials", ASTM E-119, U.L. 263 or NFPA 251. See also fire endurance.

Fire Resistive - Pertaining to the capability of withstanding fire for a specified period, usually in terms of hours with respect to temperature. Cf: fire resistance rating.

Fire Retardant - Substance or treatment, such as monoammonium sulfate, that reduces the combustibility of a material.

Fire Scenario - Description of the sequences in an actual or hypothetical fire which may be representative of a class of fires, including materials and items involved, geometry of compartment(s), detail(s) of ignition, fire spread and growth, smoke evolution, breakout from originating compartment, detection, extinguishment activities, and any other relevant factors.

Fire Science - Systematic body of knowledge and principles drawn from physics, chemistry, mathematics, engineering, administration, management and related branches of arts and sciences required in the practice of fire protection and prevention.

Fire Setting - Act of arson; starting of a fire maliciously and illegally.

Fire Stability - Ability for an element of construction, loadbearing or non loadbearing to resist collapse when exposed to a fire.

Fire Stop - Fire resistance or noncombustible material or construction installed at appropriate intervals in concealed spaces to prevent or restrict the spread of fire or smoke through walls, ceilings and the like. Syn: fire cutoff

Fire Storm - Large, rapidly developing fire ignited roughly simultaneously over a large area. Characteristically, fire generated winds become large as compared with meteorologically generated winds. There is considerable debate over the conditions required for such systems or whether they have occurred. Such events apparently took place in the bombing of Hamburg, Germany during World War II and in very large forest fires.

Fire Test Exposure Severity - Measure of the degree of fire exposure; specifically in connection with ASTM Methods E-119, E-152 and E-163, the ratio of the area under the curve of average furnace temperature to the area under the standard time-temperature curve, each from the start of the test to the end or time of failure, and above the base temperatures 68°F (20°C).

Firetrap - (Colloq) Building lacking adequate exits or fire protection equipment, or one which because of interior layout presents a major hazard to life in case of fire.

Fire Suppression System - A method, device, or system to detect fire or ignition and to extinguish the fire in sufficient time to prevent aircraft structural damage and/or debilitation of personnel.

Fire Triangle - Three factors necessary for combustion: fuel, oxygen, and heat. NOTE: A fire tetrahedron has been proposed to account for chemical chain reaction in combustion processes.

Fire Whirl - Revolving mass of flame in the air caused by strong convective currents and drafts in an intense fire. Cf: fire devil.

Fixed Fire Extinguishing System (FFES) - Installation of piping, wiring devices and controls fixed to the structure for the purpose of remotely applying a suitable fire extinguishing agent into a compartment or into a spot hazard. Operation may be manual or automatic.

Flame-n - Body of gas or of matter in gaseous suspension undergoing combustion and usually emitting light. v. To undergo a gaseous combustion with the emission of light.

Flame Front - Temperature and compositional microstructure associated with flames considered in a stationary reference frame.

Flame Front Thickness - Parameter giving the thickness of a flame front of combustion wave.

Flame Proofing - Surface treatment or impregnation of wood products, textiles, and other materials with fire-retardant chemicals. NOTE: The terms flame retardant and flame resistant treatment are recommended by the NFPA.

Flame Propagation - Spread of flame from region to region in a combustible material, especially in a combustible vapor-air mixture. See also: burning velocity.

Flame Resistant - Characterizing a material that does not conduct flame or continue to burn when an ignition source is removed. Cf: flame retardant.

Flame Retardance - Property of a material, or a treatment applied to a material, of retarding the propagation of flame.

Flame Retardant - Flame inhibiting chemical compound, such as inorganic salts, Lewis acids or free radical inhibitors, used on surfaces as well as in bulk to reduce the flammability of a product or structure. Flame retardants are used on textiles, in plastics and paints. NOTE: Surface treatments include glazes, such as sodium silicate or borax; coatings that evolve inert gas when heated; endothermic salts that dissipate heat or carry it away; chemicals that produce carbon dioxide and water; and intumescent paints that form an insulating carbonaceous blanket over a surface exposed to high heat.

Flame Spread - Propagation of flame over a surface.

Flame Spread Index - Product of the flame spread factor and the heat evolution factor as given in the Radiant Panel Test, ASTM E-162. Cf: flame spread classification.

Flame Spread Classification - Number indicating the relative rate at which flame spreads over the surface of a given material as compared with a scale on which flame spread over asbestos board is zero and over red oak is 100 (flame travels 3.56 fpm on red oak). The number is obtained by test in a Steiner tunnel and is a relative index and not the actual rate of flame spread nor of the fire resistance of a material. Should be used only in reference to ASTM E-84, U.L. 723 or NFPA 255. NOTE: The NFPA flame spread classes are A, 0 - 25; B, 26 - 75; C, 76 - 200; D, 201 - 500; and E, >500. Syn: flame spread rating.

Flame Temperature - Measured or calculated intensity of heat of a flame. Flame temperature can be calculated on the basis of thermodynamic considerations, assuming that the flame is an overall adiabatic process. A straightforward calculation is difficult because the high temperatures produce appreciable radical and atom concentrations and the usual stoichiometric equations become poor approximations. Flame temperature calculations are tedious when done by hand, but computer programs are available that make these computations easily and economically. There is generally good agreement between such calculated temperatures and measured flame temperatures. Also called: adiabatic flame temperature.

Flame Trap - Device consisting of screens or grids spaced closer than the quenching distance so that flame propagation stops but gas is allowed to flow through. The principle was discovered by Davey and was used in his miner's safety lamp.

Flame Velocity - See burning velocity.

Flammability - Capacity or tendency of a substance or material to burn with a flame. Syn: inflammability.

Flammability Limits - Maximum and minimum combustible gas in air concentrations which are capable of propagating flame. The lower (lean) limit is the point of fuel deficiency, the upper (rich) limit is the point of oxidizer deficiency to sustain combustion. These limits are dependent upon temperature and pressure. Cf: explosion limits; temperature limits of flammability.

Flammability Range - Scale of mixture ratios between the upper and lower flammability limits. Syn: explosive range. NOTE: As an example, the flammability range of acetylene is 2.5 to 80% by volume with air; for gasoline, the range is 1.6 to 6.0%.

Flammable - Capable of burning with a flame. Easily ignited or highly combustible. Syn: inflammable. Ant: nonflammable.

Flammable Liquid - Liquid that has a flash point below 140°F and a vapor pressure not exceeding 40 psia at 100°F. In contrast, a combustible liquid is one that has a flash point above 140°F. According to the flash point classification scheme a flammable liquid is Class I or II, while combustible liquid is Class III. Sometimes in fire practice a flammable liquid is loosely defined as one that ignites and burns at temperatures below 100°F. See flash point.

Flare-up - Sudden eruption or outburst of flame.

Flashback - Propagation of a flame from an ignition source to a supply of flammable liquid. The vapor of the liquid acts as a fuse to carry the flame. Syn: reflash.

Flash Burn - Burn injury sustained from a brief exposure to intense radiation.

Flash Fire - Fire that spreads with extreme rapidity; Fire racing through flammable substances such as flammable liquids or gases.

Flashover - Stage in the development of a contained fire in which flame spreads suddenly through the space and flames appear on all exposed surfaces.

Flash Point - Minimum temperature at which a liquid vaporizes sufficiently to form an ignitable mixture with air. Flash points are determined in the laboratory by cup tests. NOTE: In fire practice flammable liquids are sometimes classified as high and low flash point liquids depending on whether they flash above or below 37.8°C (100°F). To facilitate the management and extinguishment of flammable and combustible liquids, they have been divided into flash point classes; Classes I and II called flammable and Class III combustible liquids:

Class I - Liquids having flash points below 37.8°C (100°F).

Class IA - Those having flash points below 22.8°C (73°F) and bp below 100°F.

Class IB - Those having flash point below 22.8°C and bp at or above 37.8°C.

Class IC - Those having flash point at or above 22.8°C and bp below 37.8°C.

Class II - Liquids having flash points at or above 37.8°C and below 60°C (140°F).

Class III - Liquids having flash points at or above 60°C.

Flick - Small, easily extinguished fire.

Free Burning - Unrestricted combustion of flammable materials.

Fuel - Combustible material.

Fuel Tank Inerting - A method or system utilizing noncombustible gases such as nitrogen to preclude combustible fuel and air mixtures, and thus prevent fire and explosion.

Glowing Combustion - Oxidation of solid material with light but without a visible flame. Syn: glowing.

Group Fire - Extensive fire involving several buildings, usually in the same block and threatening to spread to neighboring blocks. Cf: conflagration, mass fire.

Hangover Fire - Holdover fire.

Heat - Kinetic energy communicable from one body to another by conduction, convection of radiation; sensation of an increase in temperature.

Holdover Fire - Fire that remains dormant for a long period of time. Syn: hangover fire, sleeper fire.

Hot Spot - Particularly active part of a fire.

Hot Surface Ignition Temperature - Generally associated with the lowest surface temperature which upon application of a flammable or combustible fluid results in sustained combustion in air. Specific hot surface ignition temperature value for particular fluid is influenced by many factors such as type and composition of surface, surface area, fluid application mode and rate extent of ventilation.

Hypergolic - Referring to substances that ignite spontaneously when mixed with each other.

Hypoxia - Oxygen want or deficiency in living tissue; state in which a physiologically inadequate amount of oxygen is available to or utilized by tissue.

Ignite - To initiate combustion.

Ignition - Initiation of combustion as evidenced by glow, flame or explosion.

Igition Energy - Quantity of heat or electrical energy that must be absorbed by a substance to ignite and burn.

Ignition Source - Any component which could precipitate a fire or explosion.

Ignition Temperature - Lowest temperature at which sustained combustion of a substance can be initiated in air.

Incandescence - Emission of light by a substance due to its high temperature.

Incombustible - Noncombustible (in air).

Induction Period - Time required by combustibles before oxidation and burning can proceed independently of heat or energy input (under certain conditions may vary from milli-seconds to months.)

Inflammable - Flammable (a misnomer).

Inhibition - Reduction of a fire or flame by the introduction of a chemical which interferes with the flame reactions. Examples are freons and sodium bicarbonate. Inhibition implies reduction in burning; extinction means carrying inhibition to completion or no fire.

Integral Tank - Aircraft structure which serves the dual purpose of carrying structural loads and confining liquids within a cavity formed by this structure.

Integrity - Ability of a separating element of construction when exposed to fire on a side to prevent the passage through it of flames and hot gases or the occurrence of flames on the unexposed side.

Intumescent Paint - A coating applied as a paint to a surface to protect it from flame or heat; produces an insulating, fire resistant foam upon exposure to heat.

Irritant - Any substance that has a major effect on living tissue; capacity to injure or stimulate cells at the application site.

Jet Fuels - Jet aircraft fuels can be classed as low or high volatility petroleum mixture. The low volatility grades are typically kerosenes, such as Jet A-1, JP-8 and JP-5. The high volatility grades are blends of kerosene and aviation gasoline (Av gas) such as JP-4, Jet B and AVTAG. Specific NATO designation, product description commonly used nomenclature and applicable specifications are as follows:

NATO CODE NUMBER	PRODUCT DESCRIPTION	COMMONLY USED NOMENCLATURE
F-34	Turbine Fuel, Aviation: Kerosene Type + Fuel System Icing Inhibitor	JP-8[1], AVTUR[2]
F-35	Turbine Fuel, Aviation: Kerosene Type	Jet A-1[3]; AVTUR[4]
F-40	Turbine Fuel, Aviation: Wide-cut Type	JP-4[5] Jet B[3] AVTAG[6]
F-44	Turbine Fuel, Aviation: High Flash Type	JP-5[5]; AVCAT[7]

1 Mil-T-83133
2 D.Eng.RD 2453
3 ASTM D1655
4 D.Eng.RD 2494
5 Mil-T-5624
6 D.Eng.RD 2454
7 D.Eng.RD 2452

Kindling Temperature - The lowest temperature at which a substance ignites. Syn: ignition temperature.

Knock Down - 1. To reduce flame and dissipate heat to prevent fire spread. 2. Initial phase of fire fighting in which flame and heat are drastically reduced to bring the fire under control.

LC_{50} - Calculated concentration, usually atmospheric, of a chemical that is expected to produce death in 50% of the biological specimens exposed; median lethal concentration.

LD_{50} - Calculated dose of a chemical or other agent that is expected to produce death in 50% of the biological specimens exposed to it.

Limited-Combustible Material - (As applied to building construction material.) Material which, in the form in which it is used, does not have a potential heat value exceeding 3500 BTU per pound, and falls into one of the following groups a. through c. No material which is subject to increase in combustibility or flame spread rating beyond these limits through the effect of age, moisture, or other atmospheric condition shall be classed as a limited-combustible material.

a. Material no part of which will ignite when subjected to fire. Any material which liberates flammable gas when heated to any temperature up to 1380°F for five minutes shall not be considered as a limited-combustion material within the meaning of this group.

b. Material having a structural base of material as described in a., with a surfacing not exceeding a thickness of 1/8 of an inch, which has a flame spread rating not greater than 50.

c. Material in the form and thickness used, other than as described in a. or b., having a flame spread rating not greater than 25 without evidence of continued progressive combustion and of such composition that surfaces that would be exposed by cutting through the material on any plane would not have a flame spread rating greater than 25 without evidence of continued progressive combustion.

Limiting Oxygen Index (L.O.I.) - The lowest oxygen concentration in an oxygen-nitrogen mixture at which a substance will continue to burn by itself. Actually $N = \frac{O_2}{N_2 + N_2}$, but usually cited as a whole number, e.g., 28. See ASTM D-2863 for procedure. Also, oxygen index.

Lower Limit of Flammability - Lowest percent concentration by volume of a flammable vapor or gas mixed with air that will ignite and burn.

Mass Fire - Fire involving many buildings or structures or a large forest fire. Not a precise term as includes "group fire", "conflagration" or "fire storm".

Mushrooming - Rapid upward and lateral extension of a fire.

Narcosis - Profound stupor, unconsciousness or arrested activity.

Noncombustibility - Property of a material to withstand high temperature without igntion. As applied to elementary materials of which building materials are composed, it can be measured by the methods and to the criteria defined in ASTM Method E-136, Test for Noncombustibility of Elementary Materials.

Noncombustible - Non-burnible or non-ignitible.

Noncombustible Construction - Structure that does not ignite or spread flame readily when exposed to fire.

Nonflammable - Not liable to ignite or burn when exposed to flame. Cf: noncombustible.

Oxygen Index - Limiting oxygen index.

Phase One or First Phase - Smoldering interior fire of ordinary combustibles with oxygen content of atmosphere approximately normal.

Phase Two or Second Phase - Flame production period of an interior fire of ordinary combustibles with oxygen content of atmosphere ranging from 21 to 15%.

Phase Three of Third Phase - Dangerous smoldering period of an interior fire with oxygen content of atmosphere below 15% and an explosion is possible if outside air is suddenly admitted.

Potential Heat Value - Average value, in BTU per pound or in BTU per square foot, obtained by testing a building material in accordance with the Tentative Method of Test for Potential Heat of Materials in Building Fires (ASTM Special Technical Publication 464, 1970, pp. 147-152). Cf: fire load.

PPM - Parts per million.

Preburn Time - Period between ignition and start of extinguishment (of fire).

Premixed Laminar Flame - Flame in which the fuel and oxidizer are mixed prior to combustion and the flow is laminar, e.g., Bunsen burner flame.

Pulmonary Edema - Fluid in the air sacs and interstitial tissue of the lungs.

Pyrolysis - Irreversible chemical decomposition due to an increase in temperature without oxygen reaction.

Quick Burner - Structure that burns rapidly in case of fire due to poor construction, combustible contents or vertical openings. Cf: firetrap.

Ramp Fire - Any fire in an aircraft while it is on the ground, i.e. before takeoff or after successful landing and including when under construction or repair-maintenance-storage.

Rate of Heat Release - Amount of heat released by a burning body in unit time.

Reburn - 1. Reignition of a burned over area in which remaining combustible fuel is rekindled when burning conditions become more favorable. 2. Area that burned a second time.

Retardant - Fire retardant.

Running Fire - Fire that advances rapidly in a given direction with a well defined head.

Scorching - Pyrolysis or partial combustion of a surface.

Sear - Scorch or cause a surface burn.

Seat of Fire - Main body of a fire; fire area producing most of the heat, flames and gases. Cf: body of fire.

Self-extinguishing - Incapable of sustained combustion in air after removal of external heat or flame.

Self-ignition - Ignition resulting from self- or spontaneous heating. Syn: spontaneous ignition.

Self-ignition Temperature - Temperature at which a substance will ignite without an external ignition source.

Self-propagation of Flame - Propagation of a flame along a solid without externally applied heat.

Sleeper Fire - Holdover fire.

Slow Combustion - Smoldering.

Smoke - Fine (0.01 to 5 micron) dispersion in air of particles of carbon and other solids and liquids of incomplete combustion. See: Ringelmann Chart, N.B.S. Smoke Test.

Smoke Damper - Device like a fire damper but intended primarily to restrict the passage of smoke and other products of combustion.

Smoldering - Combustion without flame but usually with incandescence and moderate smoke.

Smother - To extinguish a fire by blocking the oxygen supply or limiting it to a point below that required for combustion.

Snuff - 1. Smother. 2. Charred portion of candlewick.

Spark - Small, incandescent particle.

Spill Fire - Combustion of spilled liquid.

Spontaneous Combustion - Misnomer - See spontaneous ignition.

Spontaneous Heating - Self heat buildup by oxidation or fermentation. May lead to spontaneous ignition.

Spontaneous Ignition - Initiation of combustion of a material by spontaneous heating.

Sprinklered - Equipped with an approved manual or automatic sprinkler system; fixed fire extinguishing system using water in spray form as the fire extinguishing agent. Foaming or surfactant additives may be used to increase the effectiveness for special hazards.

Standard time-temperature Curve - Prescribed table of temperatures at progressing time, from the start of a fire tests, for the exposing fire; that given in ASTM Method E-119, unless specified otherwise.

Starvation - 1. Oxygen deprivation. 2. Fire extinguishment by limiting the fuel or oxidizer.

Steiner Tunnel - An 17 1/2 by 12 inch rectangular duct in which a 25 foot sample of material is tested to determine its flame spread characteristics as well as fuel contribution and smoke density. Syn: Underwriters' Laboratory 25 feet tunnel. See flame spread classification.

Suffocation - Interference with the entrance of air into the lungs and resultant asphyxia.

Suppression - Total work of extinguishing a fire beginning with its discovery.

Surface Fire - Combustion spreading on the surface of a material as contrasted to a deep seated fire.

Syncope - Fainting; temporary suspension of consciousness from cerebral anoxia.

Synergism - Combined action or effect of two or more agents that is greater than the sum of their individual actions.

Test Fire - Fire set to evaluate fire behavior, equipment or personnel performance, or control measures.

Temperature Limits of Flammability - Extreme limits of a temperature range within which saturated fuel vapor-air mixtures are flammable. For example, the lower and upper temperature limits for JP-4 fuel at standard atmospheric pressure are approximately -20°F and 60°F, respectively.

Threshold Limit Value (TLV) - Airborne concentration of a particular substance used to define conditions under which nearly all workers may be repeatedly exposed for a working lifetime (8 hours/day, 5 days/week) without adverse effect (value established by American Conference of Governmental Industrial Hygienists).

Touch-off - Fire believed to be of incendiary origin.

Toxicity - Harmful effect on a biological system caused by a chemical or physical agent.

Turbulent Flame - Flame propagating through a turbulent stream. Example: jet engine flame.

Upper Limit of Flammability - The highest percent concentration by volume of a flammable vapor or gas in air that will burn with a flame.

APPENDIX G

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14. Abstract

In 1976, the Propulsion and Energetics Panel of AGARD set up its Working Group 11 on "Aircraft Fire Safety". The findings and recommendations of Working Group 11 are collected in this Executive Summary which forms Volume 1 of the final Advisory Report of the Working Group. Volume 2 of the same publication contains the full report of the Working Group.

Besides the various recommendations on technical and operational subjects a strong proposal is included for an international cooperative effort in the field of aircraft fire safety.

En 1976, le Panel "Energétique et Propulsion" de l'AGARD créa le Groupe de Travail No.11 sur "La Sécurité contre les Incendies d'Avions". Les conclusions et recommandations de ce Groupe de Travail sont rassemblées dans cet "Executive Summary" qui forme le Volume 1 de la version définitive du Rapport Consultatif du Groupe de Travail. Le Volume 2 de la même publication contient le rapport complet du Groupe de Travail.

Outre diverses recommandations portant sur des points techniques et opérationnels, ce document propose avec vigueur que soit entrepris un effort de coopération à l'échelon international dans le domaine de la sécurité contre les incendies d'avions.

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